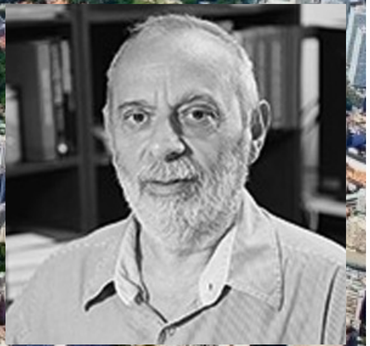
Gravitational Particle Production and Dark Matter — Four Lectures

1. Dark Matter: Evidence and the Standard WIMP
2. Gravitational Particle Production (Schrödinger's Alarming Phenomenon)
3. GPP of Scalar Fields
4. Beyond Scalar Fields



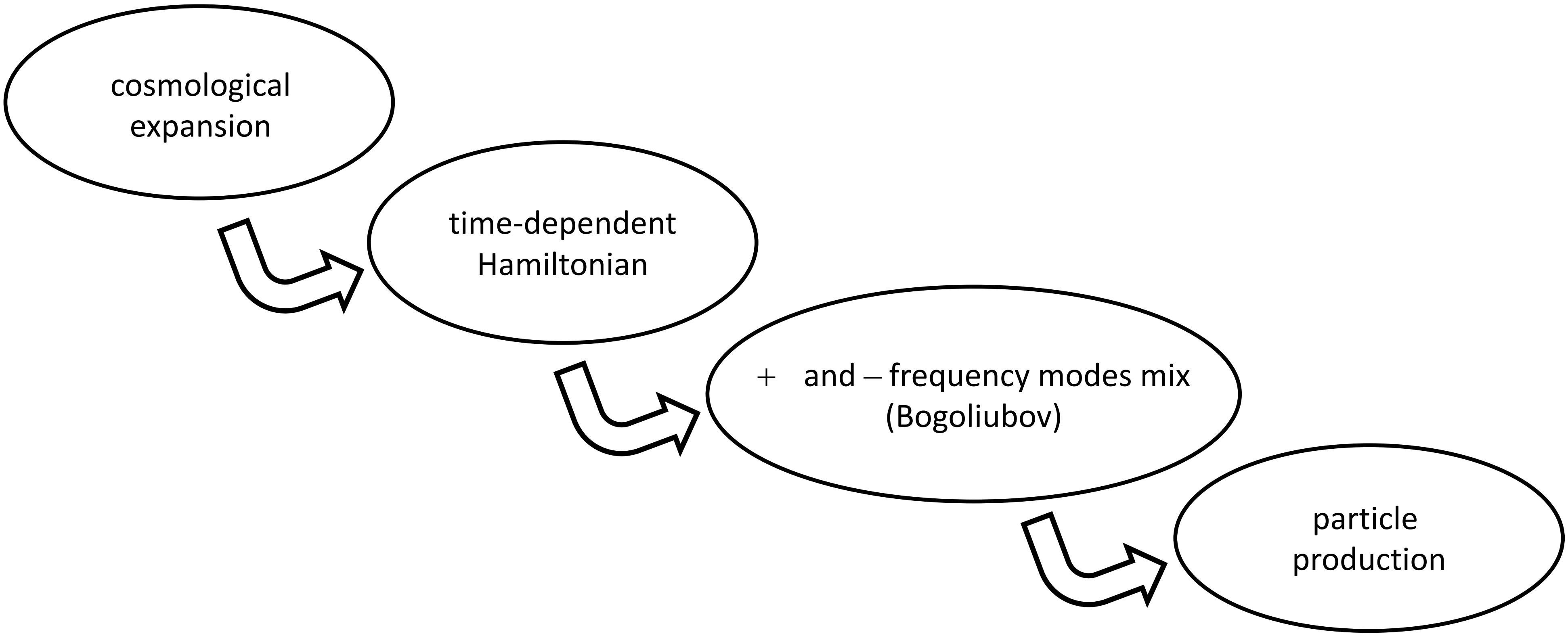
Rocky Kolb, University of Chicago

CBPF 9/2022

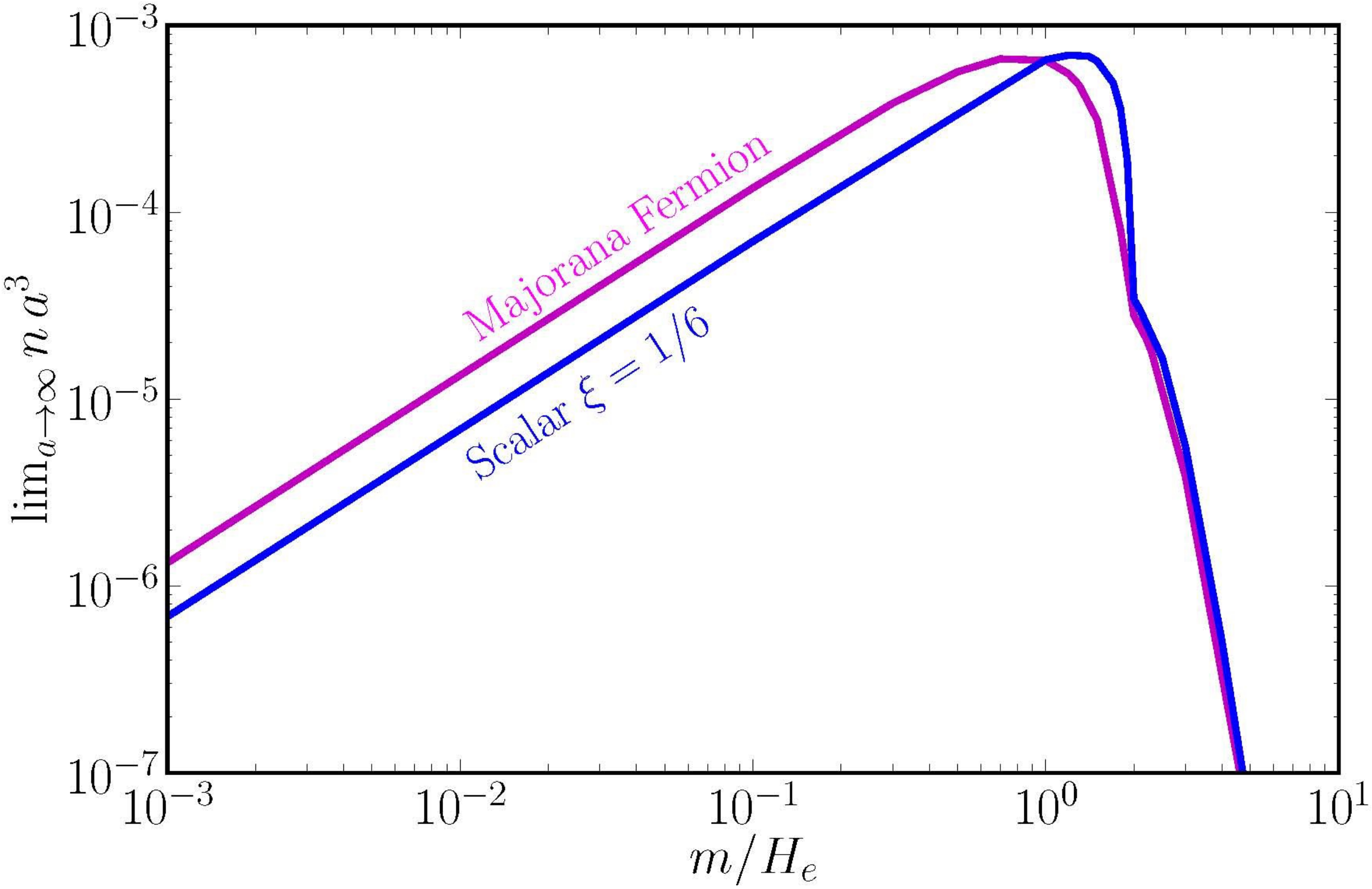
Cosmological Gravitational Particle Production (CGPP)

- In Minkowskian QFT, a particle is an IR of the Poincaré group.
- But, expanding universe not Poincaré invariant.
- Notion of a "particle" is approximate.

Schrodinger (1939); Parker (1965, 68); Fulling, Ford, & Hu; Zel'dovich; Starobinski; Grib, Frolov, Mamaev, & Mostepanenko; Mukhanov & Sasaki, Birrell & Davies…



Conformal: $\xi = 1/6$



$na^3 \to 0$ as $m \to 0$

For conformally-coupled scalar, conformal symmetry only broken by mass term.

Since metric is conformally Minkowski, massless, conformally-coupled scalar field does not feel expansion.

Conversion of na^3 to Ωh^2

After inflation universe dominated by coherent oscillations of inflaton. Energy density decreases as a matter-dominated universe. Eventually inflaton decays, “reheating” the universe to some “reheat” temperature $T_{\rm RH}$, after which the universe evolves as a radiation-dominated universe, eventually becoming matter dominated around $z = 30{,}000$, then dark-energy dominated at a redshift ≈ 1.

All the while na^3 remaining constant.

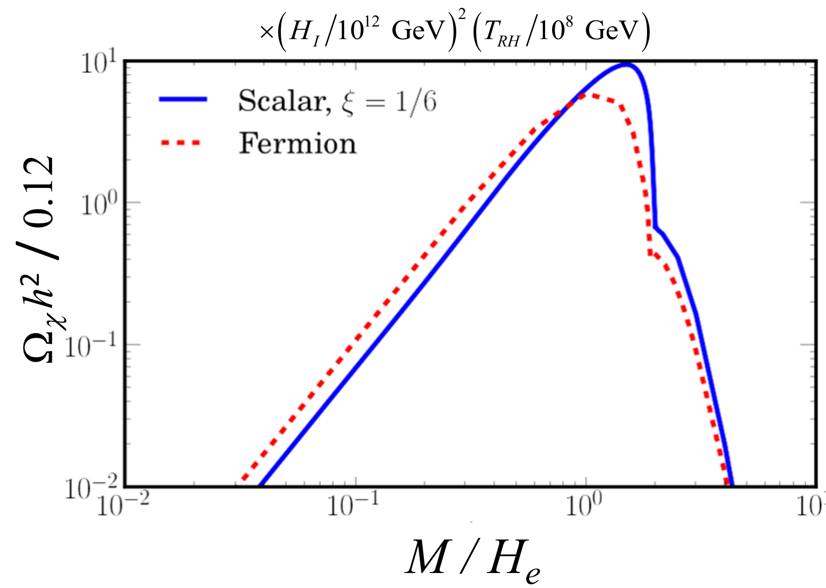
$$\frac{\Omega h^2}{0.12} = \frac{m}{H_e}\left(\frac{H_e}{10^{12}\,\mathrm{GeV}}\right)^2\left(\frac{T_{\rm RH}}{10^{9}\,\mathrm{GeV}}\right)\frac{\lim_{a\to\infty} n\,a^3}{10^{-5}}$$

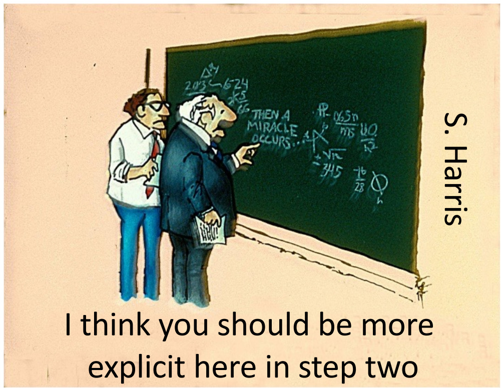
We don’t know H_e or $T_{\rm RH}$, but the above values are “representative” choices.

So $na^3 \approx 10^{-5}$ seems desirable.

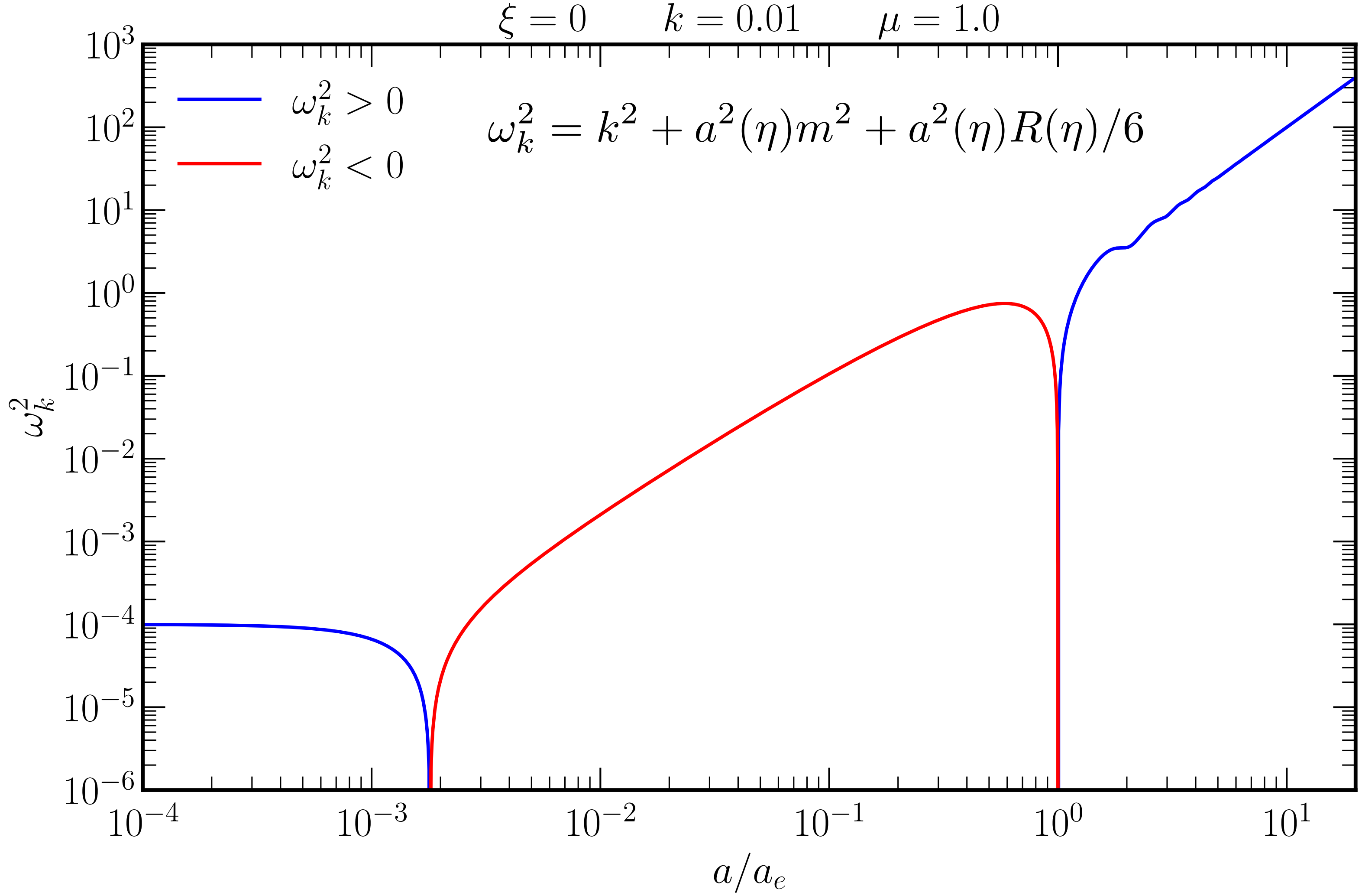
WIMPzillas

- Inflation signifies a new mass scale.
- H_e, expansion rate at end of inflation, comparable to inflaton mass.
- Expect other particles with mass comparable to inflaton mass.
- If one stable, natural candidate for dark matter (don't say WIMPzilla miracle).
- If not stable but long-lived, decays can produce entropy, baryon number, …



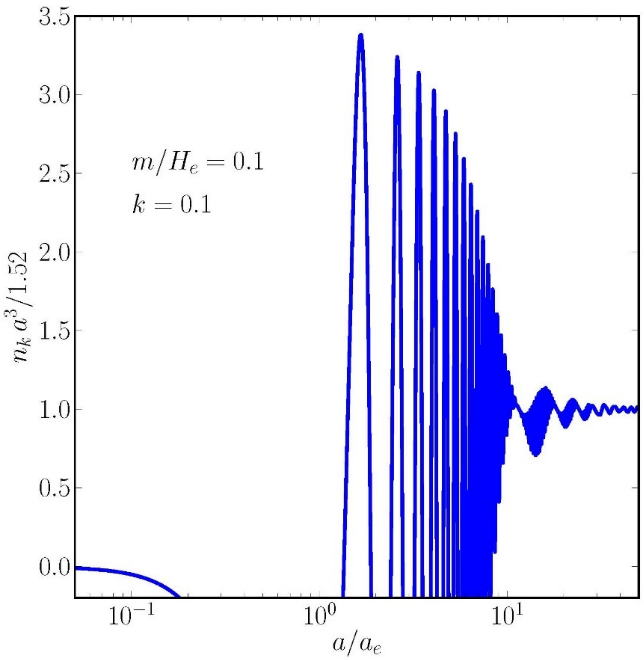


Adiabaticity Parameter A_k



Minimal: $\xi = 0$

Kolb & Long 2020



Evolution complicated by 2 frequency scales: m and R

$$\omega_k^2 = k^2 + a^2(\eta)\left(m^2 + \frac{1}{6}R(\eta)\right)$$

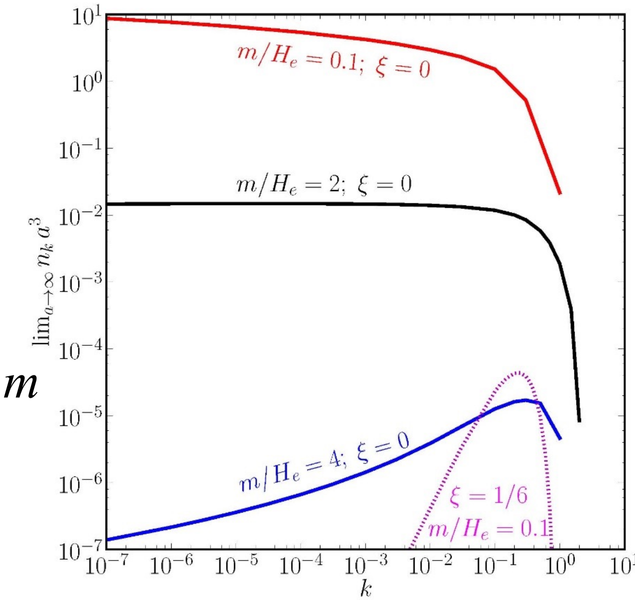
Nonadiabatic deep in inflation as mode becomes tachyonic* for small m

Irruption when tachyonic: $k = aH$

Suppression in spectrum at $k > 1$

Suppression in spectrum for $m/H_e > 1$

Kolb & Long 2020



Spectrum diverges In IR for $m / H_e < 2$

Isocurvature issues

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*In inflation $R \sim -H^2$

Scalar field in FRW background

Red Spectrum Leads to dangerous Isocurvature Fluctuations

If WIMPzillas contribute to matter density, two sources of density fluctuations:

Curvature fluctuations from inflation

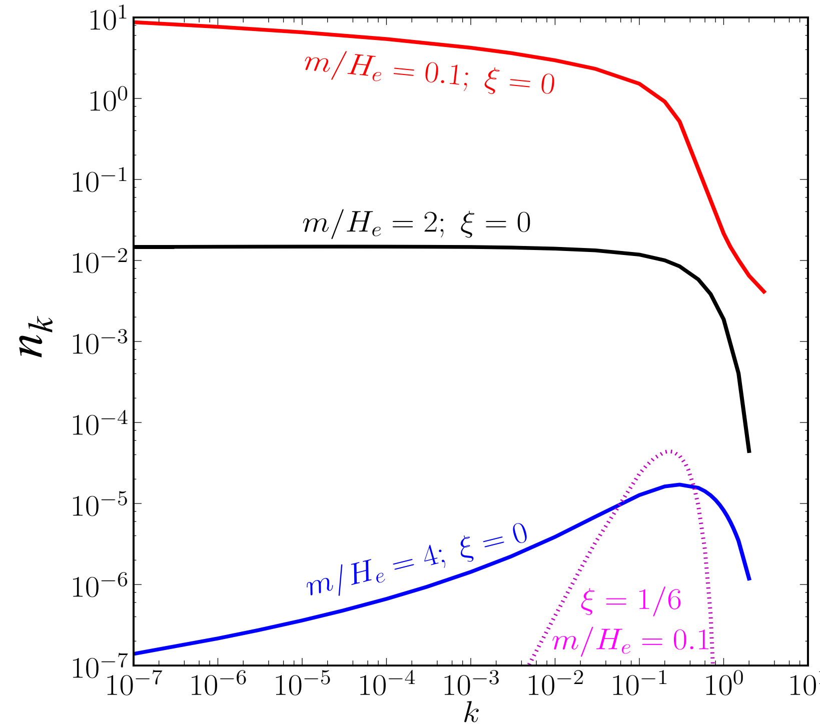
Fluctuations in χ field

They are uncorrelated.

DM density perturbations uncorrelated with baryon and photon perturbations.

For red spectrum, strict CMB limits

Chung, Kolb, Riotto, Senatore for minimally-coupled scalars



Assumes <u>before</u> reheating mode becomes

nonrelativistic $k/a < m$

and sub-Hubble $k/a < H$

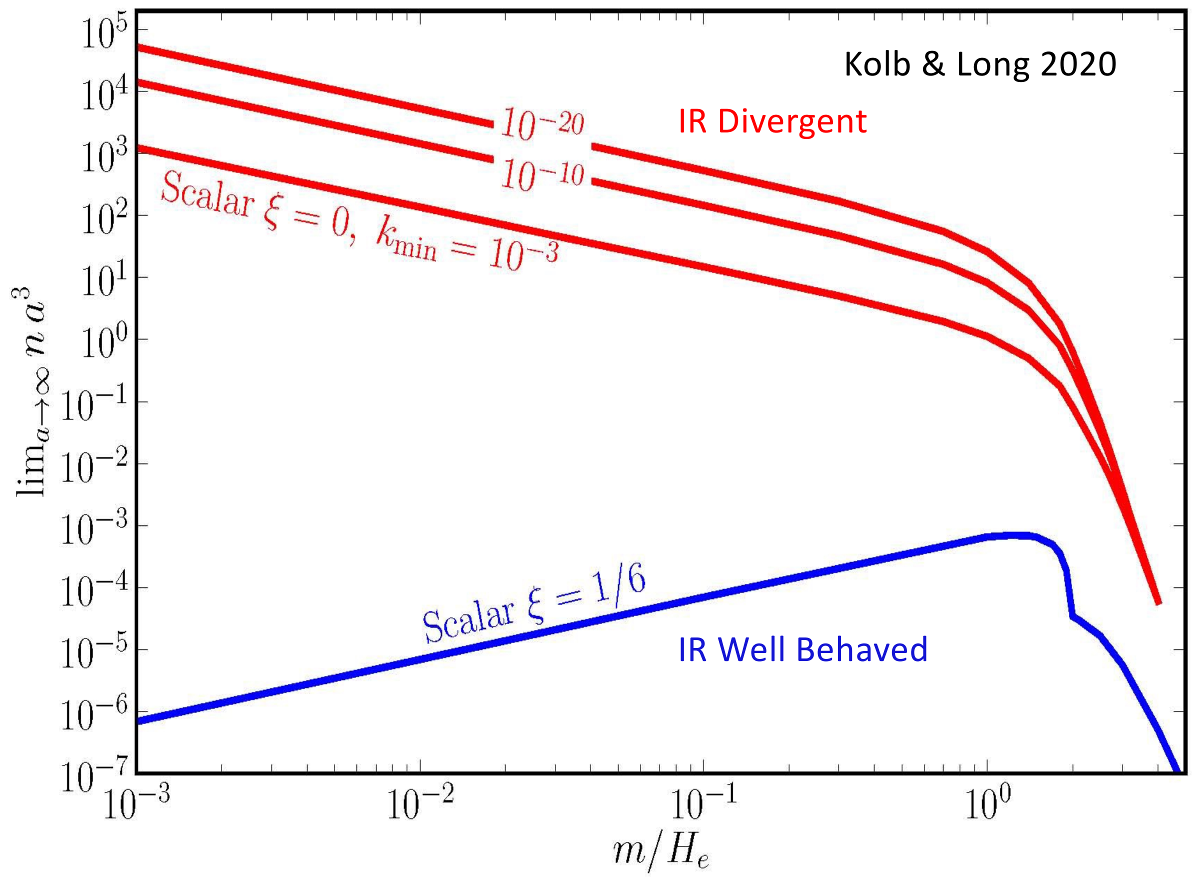
Red spectrum survives "early" reheating.

Final Number Density

- Comoving abundance $n\,a^3$ calculable in terms of H_e & m/H_e for "large" m.
- Translation of commoving abundance to present mass density has additional dependence on H_e & $T_{\rm RH}$.

$$H_e \leq 3\times 10^{14}\,\text{GeV} \quad T_{\rm RH} \geq 10^2\,\text{GeV}$$

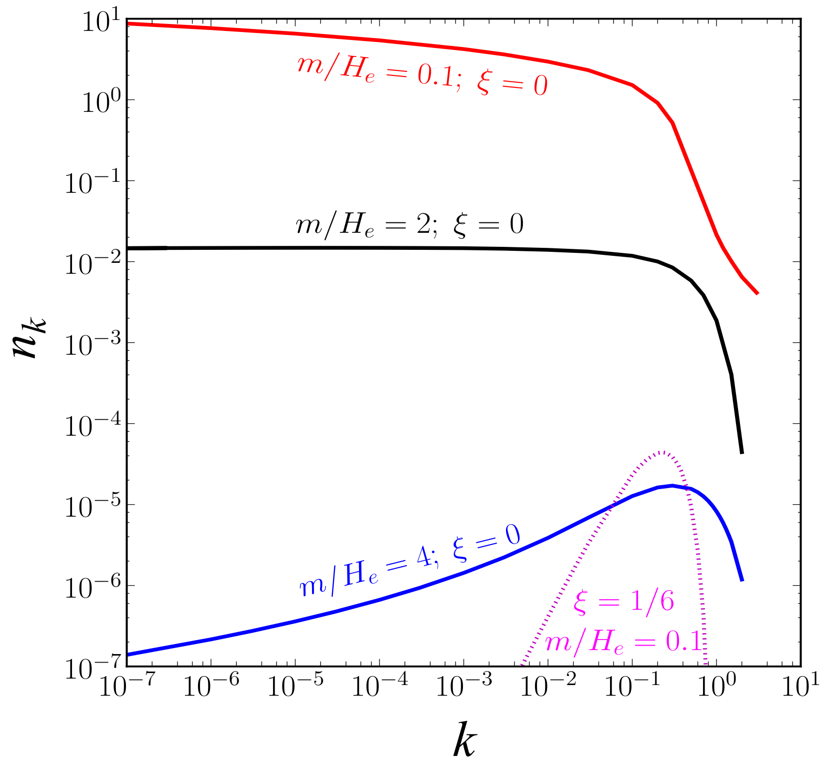
- For $m > H_e$ $\quad na^3 \propto e^{-cm/H_e}$
- For $m < H_e$,
  $n\,a^3 \sim m^{-1}$ minimally coupled
  $n\,a^3 \sim m^{+1}$ conformally coupled
- If DM candidate, require large H_e and large $T_{\rm RH}$



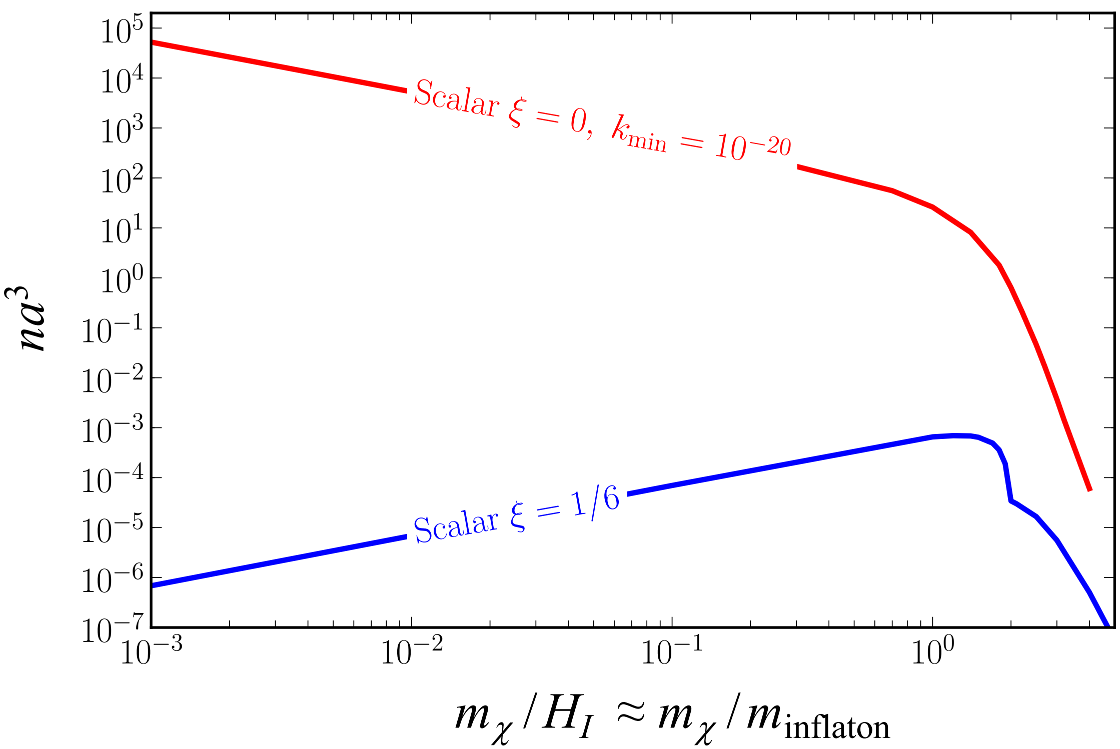
$$\frac{\Omega h^2}{0.12} = \frac{m}{H_e}\left(\frac{H_e}{10^{12}\,\text{GeV}}\right)^2\left(\frac{T_{\rm RH}}{10^9\,\text{GeV}}\right)\left[\frac{n\,a^3}{10^{-5}}\right]$$

Scalar field ϕ in FRW background

$$[na^3] = \frac{1}{2\pi^2}\int \frac{dk}{k} n_k$$



$$\frac{\Omega_\chi h^2}{0.12} = \frac{m_\chi}{H_I}\left(\frac{H_I}{10^{12}\mathrm{GeV}}\right)^2\left(\frac{T_{\mathrm{RH}}}{10^9\mathrm{GeV}}\right)\frac{[na^3]}{10^{-5}}$$



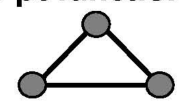
$\xi = 0$ red for $m/H_I < 2$
blue for $m/H_I > 2$

$\xi = 1/6$ blue for all m/H_I

Minimally-coupled scalar WIMPZILLA not DM candidate unless $m_\chi/H_I \approx m_\chi/m_{\mathrm{inflaton}} \gtrsim$ a few

Long-term Program

Complexity ↓

* related to but not cosmological collider program	1-pt function 	2-pt function 	3-pt function* 
Observable	**Dark Matter**	**Isocurvature Fluctuations**	**CMB Non-Gaussianities**
Massive scalar field (conformal)	Chung, Kolb, & Riotto (98) Kuzmin & Tkachev (99)	Expected to be very small	Chung & Yoo
Massive scalar field (minimal)	Kuzmin & Tkachev (99)	Chung, Kolb, Riotto & Senatore	
Massive Dirac field	Chung, Kolb & Riotto (98, 99)	Similar to conformal scalar	Similar to conformal scalar?
Proca-de Broglie field	Massive: Kolb & Long Light: Graham, Mardon & Rajendran		
Massive Rarita-Schwinger field	Kolb, McDonough, Long		
Massive Fierz-Pauli field	Kolb, Ling, Long & Rosen (in progress)		

Complexity →

Life Becomes More Interesting (More Complicated)

Set of matter fields $\{\Phi^n\}$

Stress-energy tensor: Can't use Noether stress tensor, use Belinfante-Rosenfeld stress tensor.

$$T^{\mu\nu}_{\mathrm{Noether}} = g^{\mu\nu}\mathcal{L} - \frac{\partial\mathcal{L}}{\partial(\partial_\mu\Phi^n)}\partial^\nu\Phi^n$$

not guaranteed to be symmetric in μ and ν

does not account for energy density associated with intrinsic angular momentum

$$T^{\mu\nu}_{\mathrm{Belinfante-Rosenfeld}} = -\frac{2}{\sqrt{-g}}\frac{\delta(\sqrt{-g}\mathcal{L})}{\delta g_{\mu\nu}} = 2g^{\mu\alpha}g^{\nu\beta}\frac{\partial\mathcal{L}}{\delta g^{\alpha\beta}} - \mathcal{L}g^{\mu\nu}$$

Life Becomes More Interesting (More Complicated)

Promotion of flat-space action to curved space

For scalars or vectors:

1. Replace $\eta_{\mu\nu} \longrightarrow g_{\mu\nu}$
2. Replace all tensors by objects that behave as tensors under general coordinate transformations
3. Replace derivatives by covariant derivatives $\partial_\mu \longrightarrow \nabla_\mu$

Doesn't work for half-integer spins

Must use (repéres mobiles, vierbein, tetrad, frame fields) formalism, e.g., for Dirac field

$$S[\psi,\bar{\psi}] = \int d^4x \, \det(e) \, \left\{ \frac{i}{2}\bar{\psi} e_\alpha{}^\mu \gamma^\alpha \left(\partial_\mu + \Gamma_\mu\right)\psi - \frac{i}{2}\left[\left(\partial_\mu - \Gamma_\mu\right)\bar{\psi}\right] e_\alpha{}^\mu \gamma^\alpha \psi - m\bar{\psi}\psi \right\}$$

$e_\alpha{}^\mu$ is frame field $\qquad e_\alpha{}^\mu \gamma^\alpha \longrightarrow \underline{\gamma}^\mu$

For Dark Matter, Scalar Fields Not the Only Game in Town

spin-0 (real scalar)

Chung, Kolb, & Riotto (1998); Kuzmin & Tkachev (1998)

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi - \frac{1}{2} m^2 \varphi^2 + \frac{1}{2} \xi R \varphi^2$$

spin-$1/2$ (Dirac)

Chung, Kolb, & Riotto (1998); Kuzmin & Tkachev (1998); Chung, Everett, Yoo, & Zhou (2011)

$$\mathcal{L} = \frac{i}{2} \bar{\Psi} \underline{\gamma}^\mu (\nabla_\mu \Psi) - \frac{1}{2} m \bar{\Psi} \Psi + \mathrm{h.c.}$$

spin-1 (de Broglie-Proca)

Dimopoulos (2006) – not for DM; Graham, Mardon, & Rajendran (2016); Ahmed, Grzadkowski, & Socha (2020); Kolb & Long (2020)

$$\mathcal{L} = -\frac{1}{4} g^{\mu\alpha} g^{\nu\beta} F_{\mu\nu} F_{\alpha\beta} + \frac{1}{2} m^2 g^{\mu\nu} A_\mu A_\nu - \frac{1}{2} \xi_1 R g^{\mu\nu} A_\mu A_\nu - \frac{1}{2} \xi_2 R^{\mu\nu} A_\mu A_\nu$$

spin-$3/2$ (Rarita-Schwinger)

Kallosh, Kofman, Linde, & Van Proeyen (1999)
Giudice, Riotto, & Tkachev (1999); Lemoine (1999); Kolb & Long (2020)

$$\mathcal{L} = \frac{i}{4} \bar{\Psi}_\mu \left(\underline{\gamma}^\mu \underline{\gamma}^\rho \underline{\gamma}^\sigma - \underline{\gamma}^\sigma \underline{\gamma}^\rho \underline{\gamma}^\mu \right) (\nabla_\rho \Psi_\sigma) - \frac{1}{2} m \bar{\Psi}_\mu \underline{\gamma}^\mu \underline{\gamma}^\sigma \Psi_\sigma + \mathrm{h.c.}$$

spin-2 (Fierz-Pauli)

DM: Kolb, Liang, Long & Rosen (2022); [see also Babichev, et al (2016)
Bernard, Deffayet, & von Strauss (2015); Mazuet & Volkov (2018)]

$$\mathcal{L} = \frac{1}{2} M_g^2 h_{\mu\nu} \left(\tilde{\mathcal{E}}^{\mu\nu\rho\sigma} + m^2 \mathcal{M}^{\mu\nu\rho\sigma} \right) h_{\rho\sigma}$$

Dirac field ψ in FRW background

Dirac Equation in FRW:

$$i\partial_\eta \begin{pmatrix} u_A(\eta) \\ u_B(\eta) \end{pmatrix} = \begin{pmatrix} a(\eta)m & k \\ k & -a(\eta)m \end{pmatrix} \begin{pmatrix} u_A(\eta) \\ u_B(\eta) \end{pmatrix}$$

Dispersion relation same as conformally-coupled scalar

$$\omega_k^2(\eta) = k^2 + m^2 a^2(\eta)$$

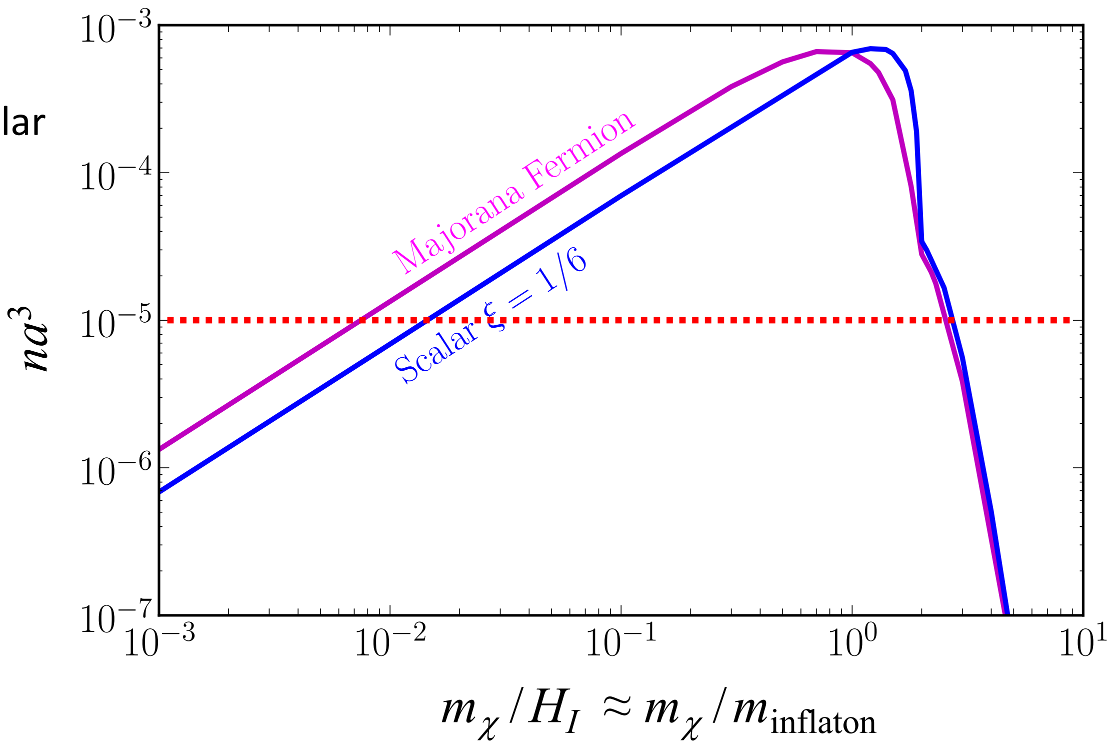
Adiabaticity parameter k/m × conformal scalar

$$A_k = \frac{a^2 H m k}{(k^2 + a^2 m^2)^{3/2}}$$

Blue spectrum: no isocurvature issues

Dirac WIMPZILLA DM candidate for $m_\chi = \mathcal{O}(m_{\text{inflaton}})$

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



Fields with Spin > 1/2

For bosons, $\omega_k(\eta)$ tells all:

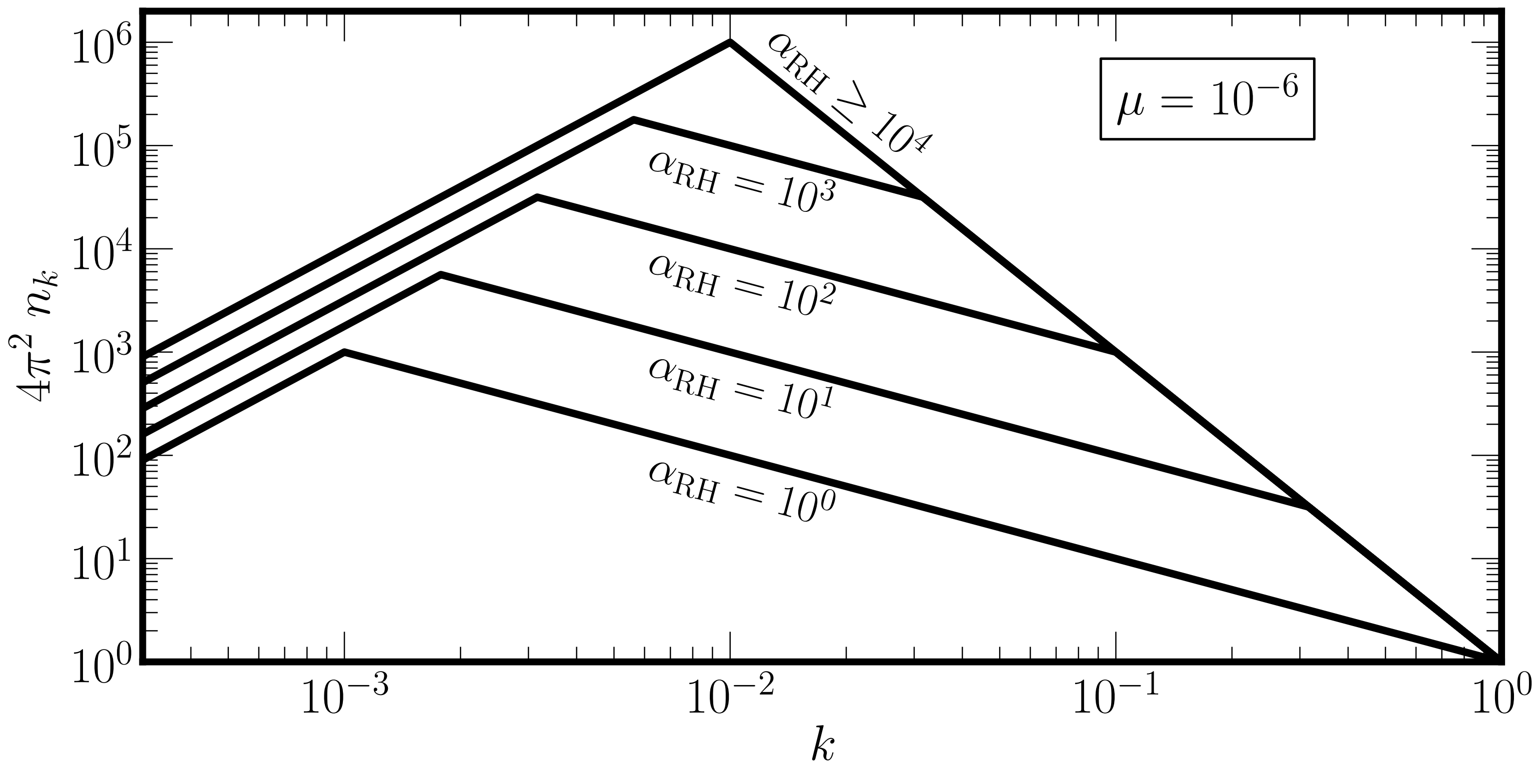
$$\omega_k^2(\eta) = \begin{cases} k^2 + a^2(\eta)m^2 + (\frac{1}{6} - \xi)a^2(\eta)R(\eta) & s=0 \\ k^2 + a^2(\eta)m^2 \quad \text{Like conformally-coupled scalar: in massless limit no production} & s=1 \quad \lambda=\pm 1 \\ k^2 + a^2(\eta)m^2 + \frac{1}{6}\frac{k^2a^2(\eta)R(\eta)}{k^2+a^2(\eta)m^2} + 3\frac{k^2a^4(\eta)H^2(\eta)m^2}{(k^2+a^2(\eta)m^2)^2} \quad \text{Interesting (i.e., complicated)} & s=1 \quad \lambda=0 \\ k^2 + a^2(\eta)m^2 + \frac{1}{6}a^2(\eta)R(\eta) \quad \text{Like minimally-coupled scalar; graviton in massless limit} & s=2 \quad \lambda=\pm 2 \\ k^2 + a^2(\eta)m^2 + \frac{1}{6}\frac{a^2(\eta)(2k^2+a^2(\eta)m^2)R(\eta)}{k^2+a^2(\eta)m^2} - \frac{a^2(\eta)k^2(2k^2-a^2(\eta)m^2)H^2(\eta)}{(k^2+a^2(\eta)m^2)^2} & s=2 \quad \lambda=\pm 1 \\ \text{way, way too long to show} & s=2 \quad \lambda=0 \end{cases}$$

de Broglie—Proca field A_μ in FRW background

Graham, Mardon, & Rajendran (2016); Ahmed, Grzadkowski, & Socha (2020); Kolb & Long (2020)

Dispersion relation for transverse modes, $\omega_k^2 = k^2 + a^2(\eta)m^2$, same as conformally-coupled scalar.

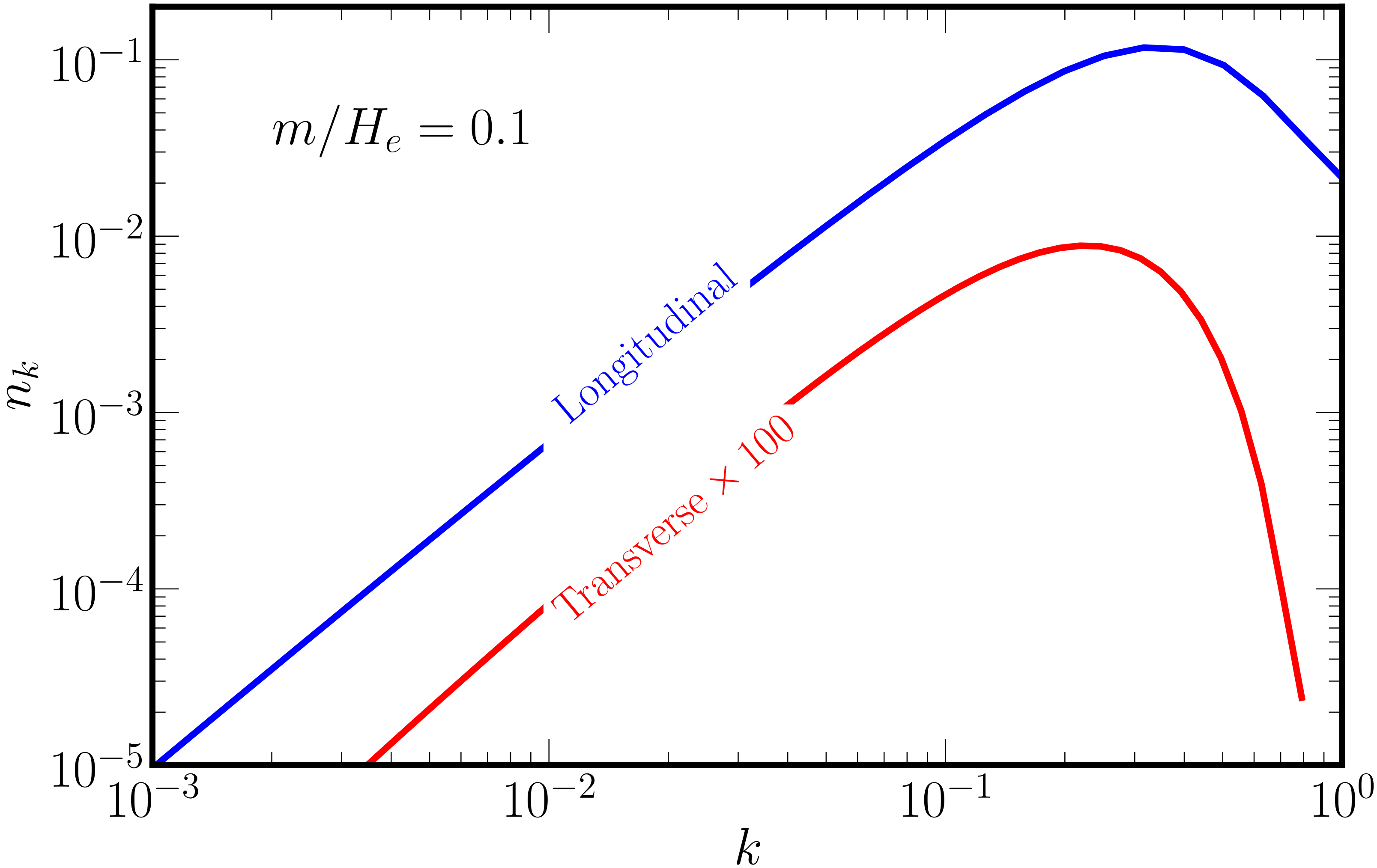
Dispersion relation for longitudinal modes, $\omega_k^2 = k^2 + a^2(\eta)m^2 + \frac{1}{6}\frac{k^2a^2(\eta)R(\eta)}{k^2+a^2(\eta)m^2} + 3\frac{k^2a^4(\eta)H^2(\eta)m^2}{(k^2+a^2(\eta)m^2)^2}$, "interesting."



$\mu = m/H_e$

$\alpha_{\rm RH} = a_{\rm RH}/a_e$

de Broglie—Proca field A_μ in FRW background



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- power spectrum is blue-tilted at low k
- negligible power at CMB scales
- no problem with isocurvature even for m << H_I

Late Reheating

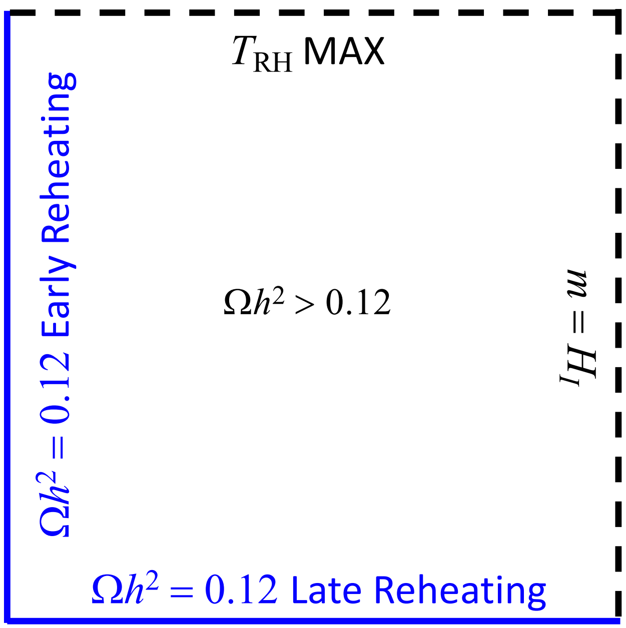
$$\frac{\Omega h^2}{0.12} = \left(\frac{H_I}{10^{11}\mathrm{GeV}}\right)^2 \left(\frac{T_{\mathrm{RH}}}{5\times 10^7\mathrm{GeV}}\right) \qquad \left(T_{\mathrm{RH}} < 8.4\times 10^8 \left(\frac{m}{\mathrm{GeV}}\right)^{1/2} \mathrm{GeV}\right)$$

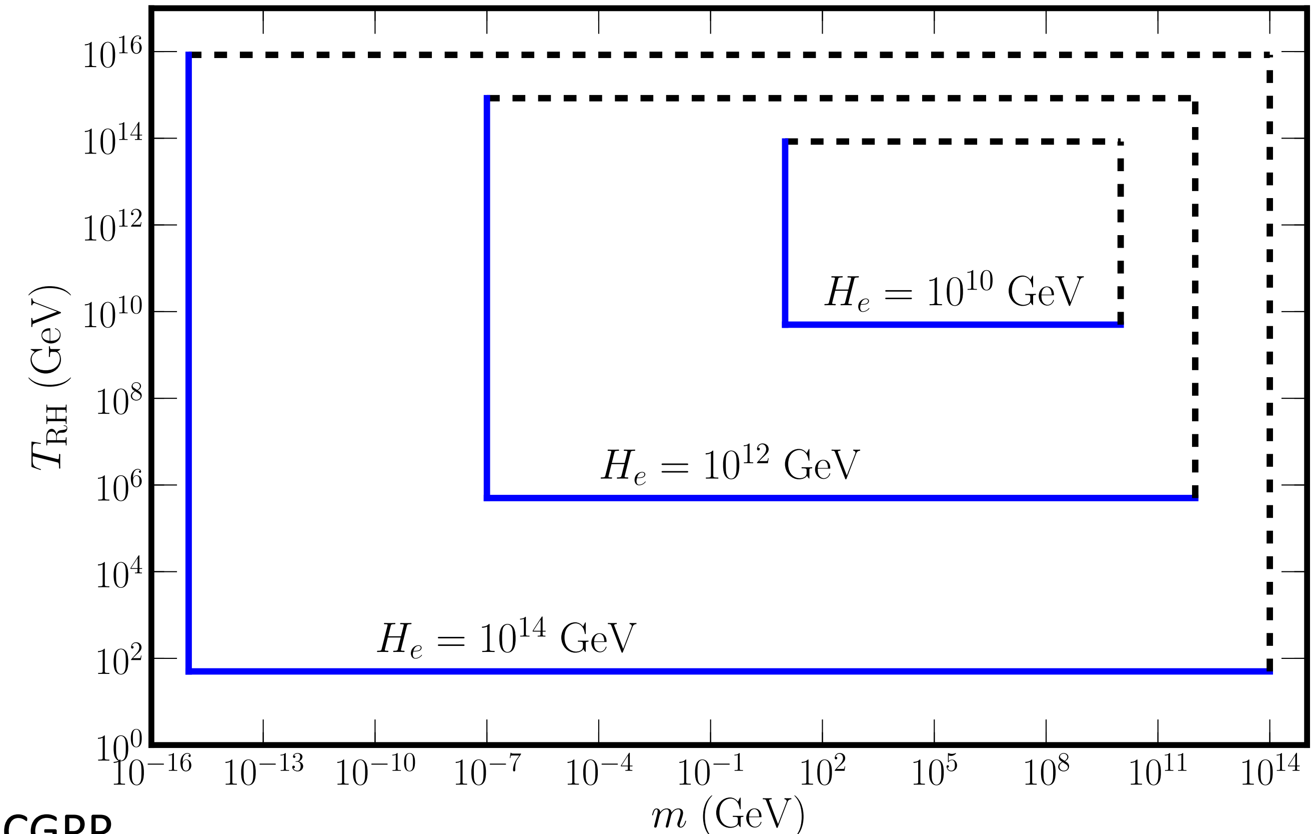
Early Reheating

$$\frac{\Omega h^2}{0.12} = \left(\frac{m}{10^{-6}\mathrm{eV}}\right)^{1/2} \left(\frac{H_I}{10^{14}\mathrm{GeV}}\right)^2 \qquad \left(T_{\mathrm{RH}} > 8.4\times 10^8 \left(\frac{m}{\mathrm{GeV}}\right)^{1/2} \mathrm{GeV}\right)$$

Ωh^2 depends on m, H_I, and T_{RH}

de Broglie—Proca field A_μ in FRW background





Kolb & Long (2020)

Very light (μeV) DM from CGPP

or

Very massive (10^{14} GeV) DM from CGPP

Fierz-Pauli field $f_{\mu\nu}$ in FRW background

- It was believed that massive gravity theories had ghostly 6th degree of freedom at the nonlinear level until de Rahm, Gabadadze & Trolly (dRGT 2011)

- Hassan & Rosen (2012) showed how to construct ghost-free "bimetric" theories with correct number of propagating d.o.f.

- We (with Ling, Long, and Rosen) are examining two massive spin-2 theories à la Hassan & Rosen

Minimal coupling

$$S[g,f,\Phi] = \int d^4x \left[m_g^2 \sqrt{-g}\, R(g) + m_f^2 \sqrt{-f}\, R(f) - 2m^4 \sqrt{-g}\, V(\mathbb{X};\beta_n) + \sqrt{-g}\, \mathcal{L}_m(g,\Phi) + \sqrt{-f}\, \mathcal{L}_m(f,\Phi) \right]$$

$$\mathbb{X}^\mu{}_\nu = \sqrt{g^{\mu\lambda} f_{\lambda\nu}}$$

Non-minimal coupling

$$S[g,f,\Phi] = \int d^4x \left[m_g^2 \sqrt{-g}\, R(g) + m_f^2 \sqrt{-f}\, R(f) - 2m^4 \sqrt{-g}\, V(\mathbb{X};\beta_n) + \sqrt{-g^{\text{eff}}}\, \mathcal{L}_m(g^{\text{eff}},\Phi) \right]$$

$$g^{\text{eff}}_{\mu\nu} = a^2 g_{\mu\nu} + 2ab(g\mathbb{X}) + b^2 f_{\mu\nu}$$

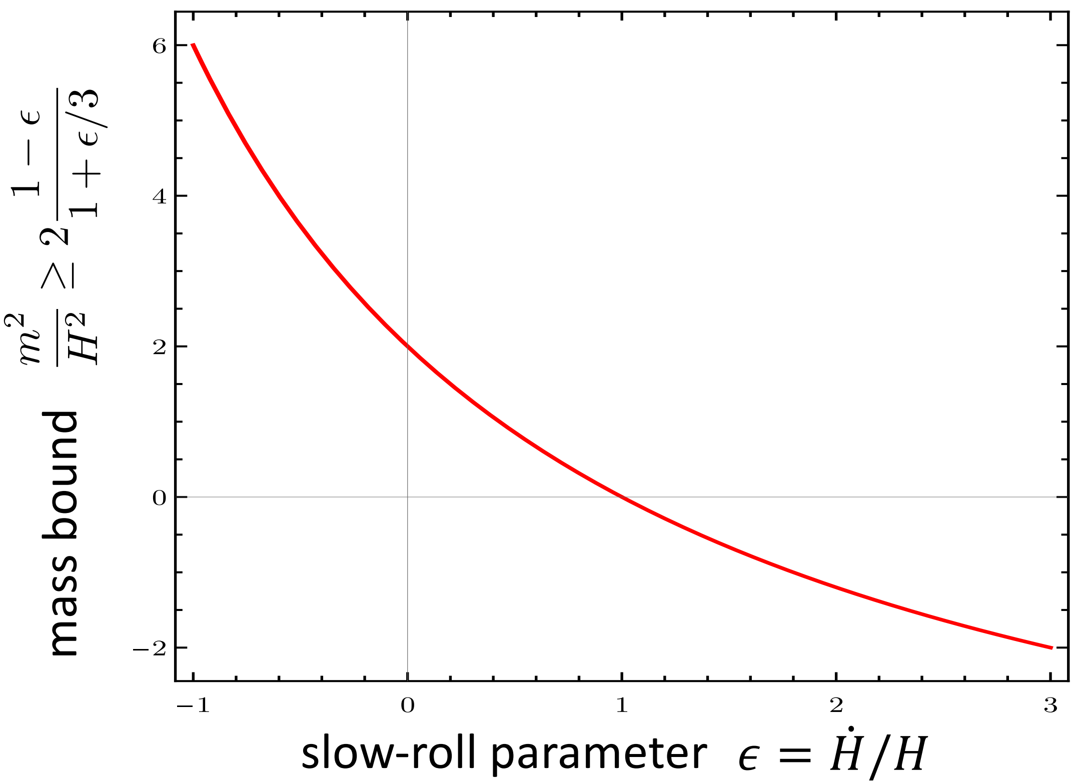
- Looking for WIMPZILLAS, but interesting things along the way

Fierz—Pauli field $f_{\mu\nu}$ in FRW background

- In 1987 Higuchi demonstrated that for fields of spin two or greater in de Sitter space, there are ghosts unless

$$m > 2H$$

- We (with Ling, Long, and Rosen) generalize the Higuchi bound to FRW:



$$m^2 \geq 2H^2 \frac{H^2 + \dot{H}}{H^2 - \dot{H}/3} = 2H^2 \frac{1-\epsilon}{1+\epsilon/3}$$

$$\epsilon = \begin{cases} 0 & \text{dS} \\ -3/2 & \text{MD} \\ -2 & \text{RD} \end{cases}$$

Cosmological Limit on the mass of massive spin-2 field!

Rarita—Schwinger field ψ_μ in FRW background

"Dirac" Equation in FRW:

$$i\partial_\eta \begin{pmatrix} u_A(\eta) \\ u_B(\eta) \end{pmatrix} = \begin{pmatrix} a(\eta)m & k \\ k & -a(\eta)m \end{pmatrix} \begin{pmatrix} u_A(\eta) \\ u_B(\eta) \end{pmatrix}$$

$s = 3/2$; $\lambda = \pm\, 3/2$ (same as $s = 1/2$)

$$i\partial_\eta \begin{pmatrix} u_A(\eta) \\ u_B(\eta) \end{pmatrix} = \begin{pmatrix} a(\eta)m & (C_A + iC_B)k \\ (C_A - iC_B)k & -a(\eta)m \end{pmatrix} \begin{pmatrix} u_A(\eta) \\ u_B(\eta) \end{pmatrix}$$

nonzero for gravitino

$s = 3/2$; $\lambda = \pm\, 1/2$

C_A & C_B function of (H, m, R, $\partial_\eta m$)

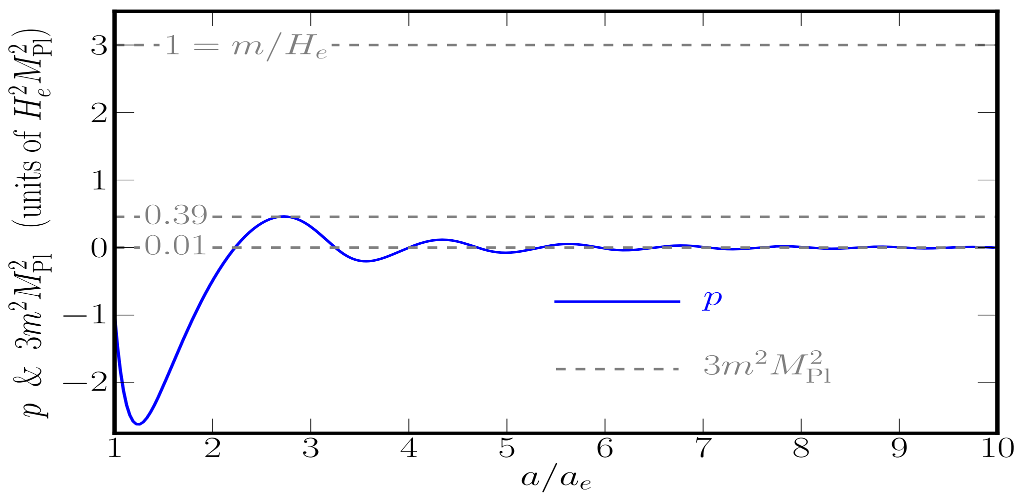
${C_A}^2 + {C_B}^2 = {c_s}^2 =$ sound speed

New feature: $$c_s = \frac{\left|p(\eta) - 3m^2 M_{\rm Pl}^2\right|}{\rho(\eta) + 3m^2 M_{\rm Pl}^2}$$ time-dependent effective sound speed!

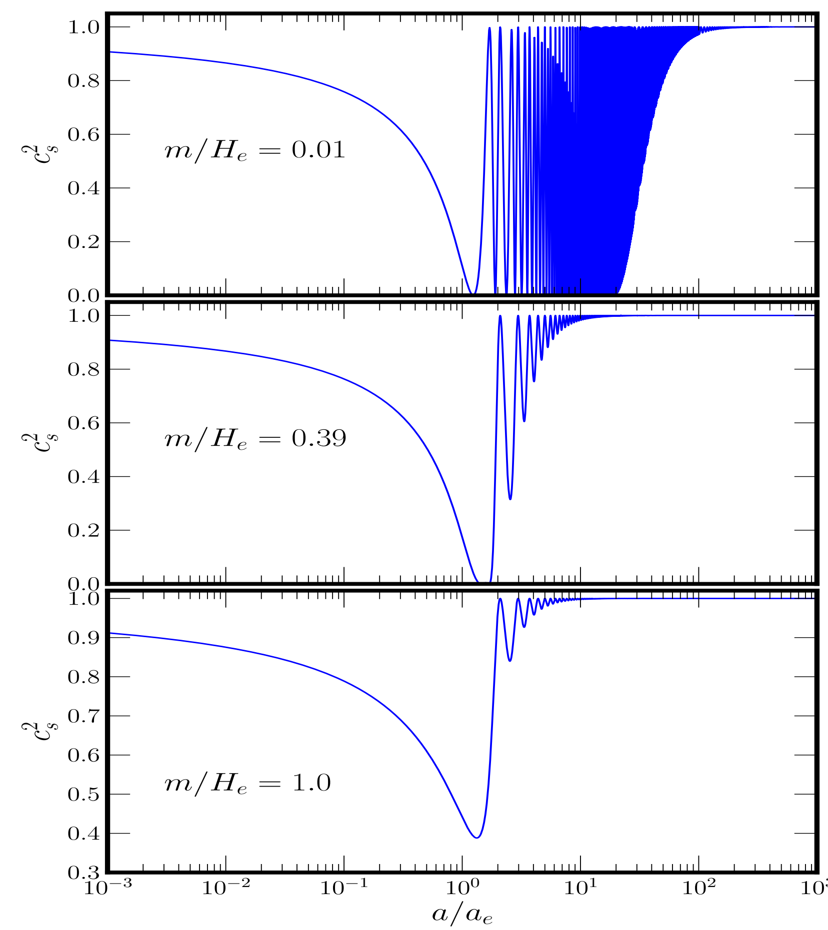
Can vanish when $p = 3m^2 M_{\rm Pl}^2$!!

Rarita—Schwinger field ψ_μ in FRW background

$$c_s = \frac{\left|p(\eta) - 3m^2 M_{\rm Pl}^2\right|}{\rho(\eta) + 3m^2 M_{\rm Pl}^2}$$



vanishing sound speed



Sound speed will vanish (perhaps many times) if $m < 0.39\ H_e$
(assumes harmonic potential after inflation)

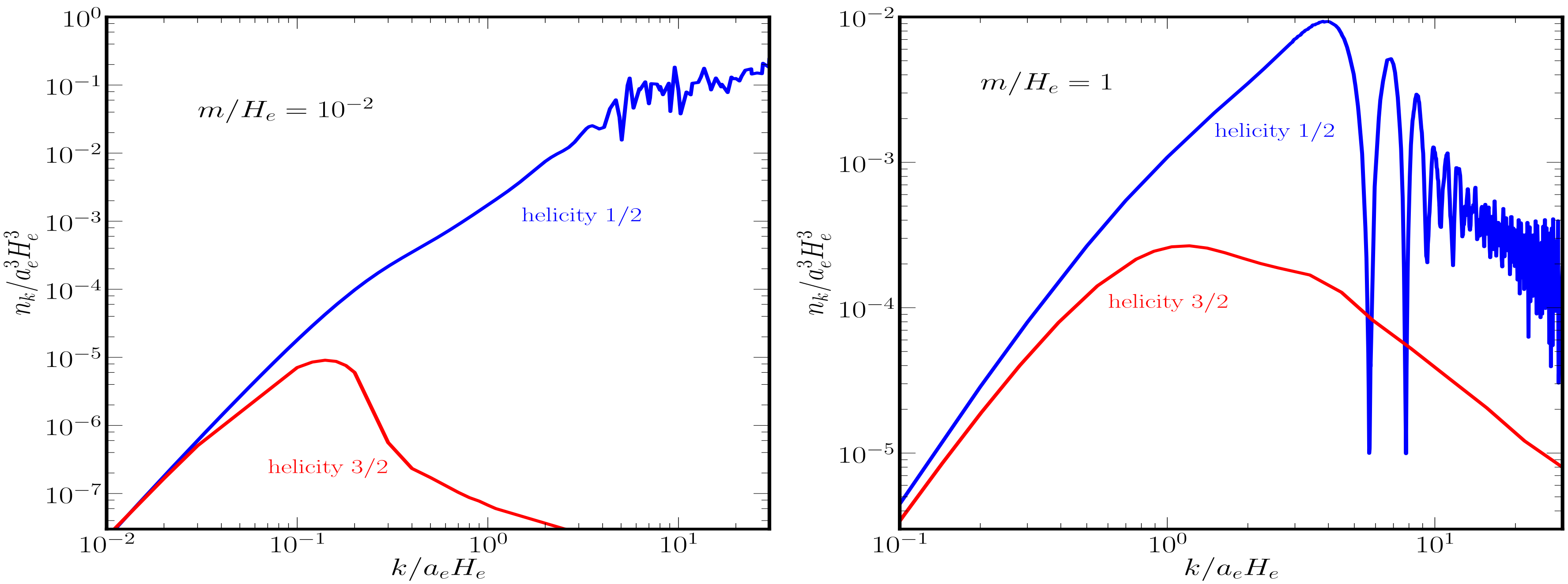
Rarita—Schwinger field ψ_μ in FRW background

Dispersion relation is $\omega_k^2(\eta) = c_s^2 k^2 + a^2(\eta) m^2$

Usual case: $c_s^2 = 1 \Rightarrow \omega_k(\eta) = k$ and constant for $k \Rightarrow \infty$

GPP depends on changing $\omega_k(\eta)$, so no production of high-k modes!

If $c_s^2 = 0$: as $k \Rightarrow \infty$, $\omega_k(\eta)$ is independent of k, production of high-k modes unsuppressed!



Rarita—Schwinger field ψ_μ in FRW background

Supergravity employs spin-3/2 field (gravitino, inflation, …), the superpartner to graviton.

Catastrophic production of gravitinos dependent on model.

For models with a single chiral superfield gravitino mass is time dependent ($\partial_\eta m \neq 0$).

$c_s = 1$ at all times $\Longrightarrow$ no catastrophic production

For models with multiple chiral superfields (most modern models)

c_s depends on relative orientation of inflaton direction & susy breaking

$c_s = 0$ in models with a nilpotent superfield and orthogonal constraint KKLT

mixing between the goldstino & inflatino may avoid the catastrophe (explicit calculation needed)

Dudas, Garcia, Mambrini, Olive, Peloso, & Verner (2021); Antoniadis, Benakli, & Ke (2021)

Models with $c_s = 0$ are in a SWAMPLAND! Kolb, Long, & McDonough (2021)

GPP may provide constraints on SUGRA model building.

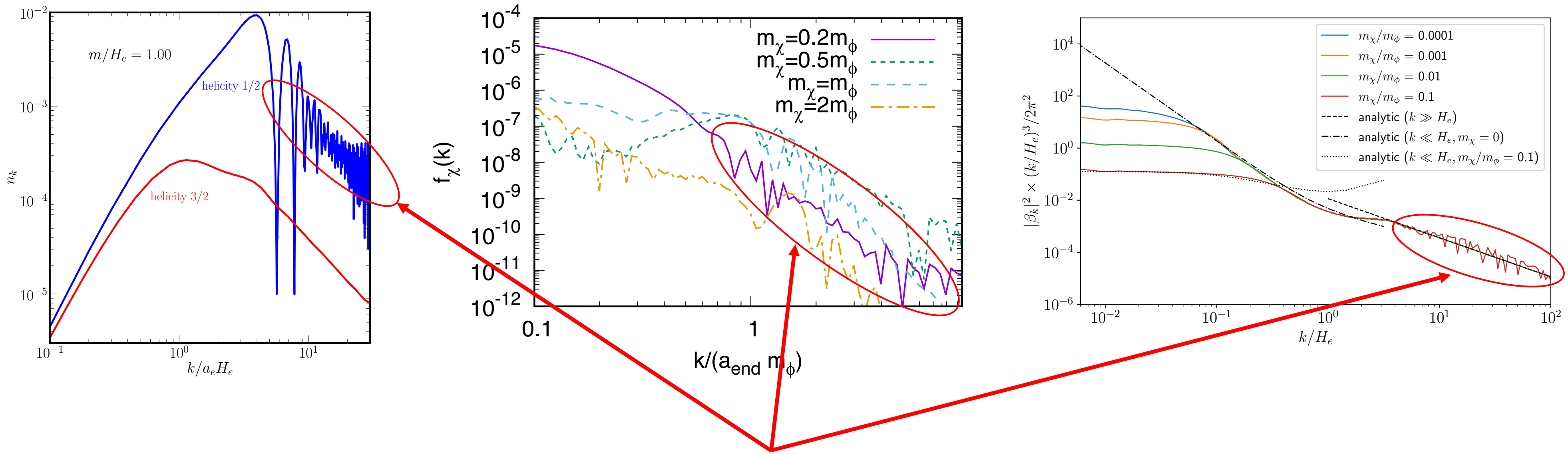
Quantum interference in gravitational particle production

(Basso, Chung, Kolb, Long)

Catastrophic Production of Slow Gravitinos
Kolb, Long, McDonough

Production of Purely Gravitational Dark Matter
Ema, Nakayama, Tang

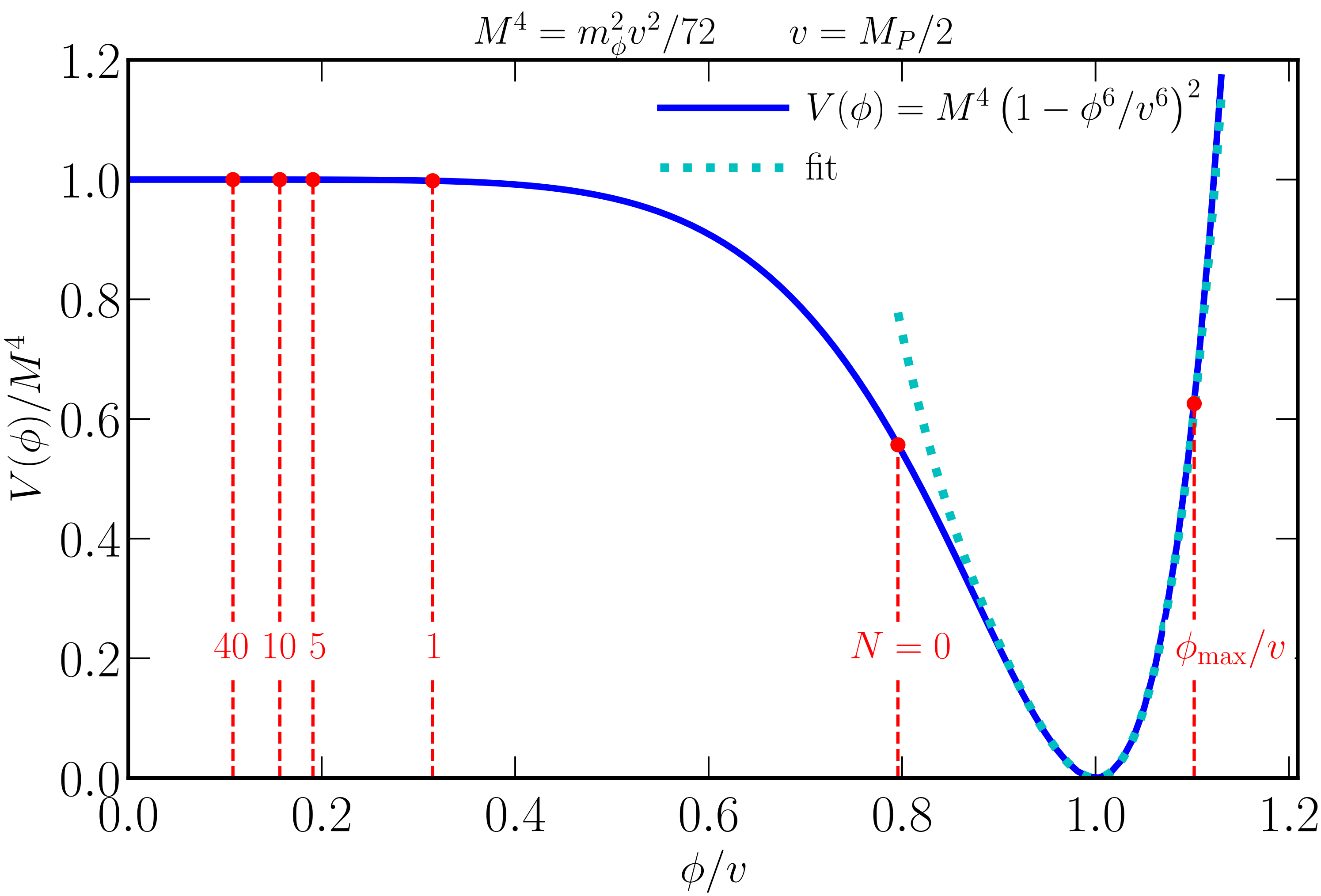
Boltzmann or Bogoliubov?
Kaneta, Mook, Oda

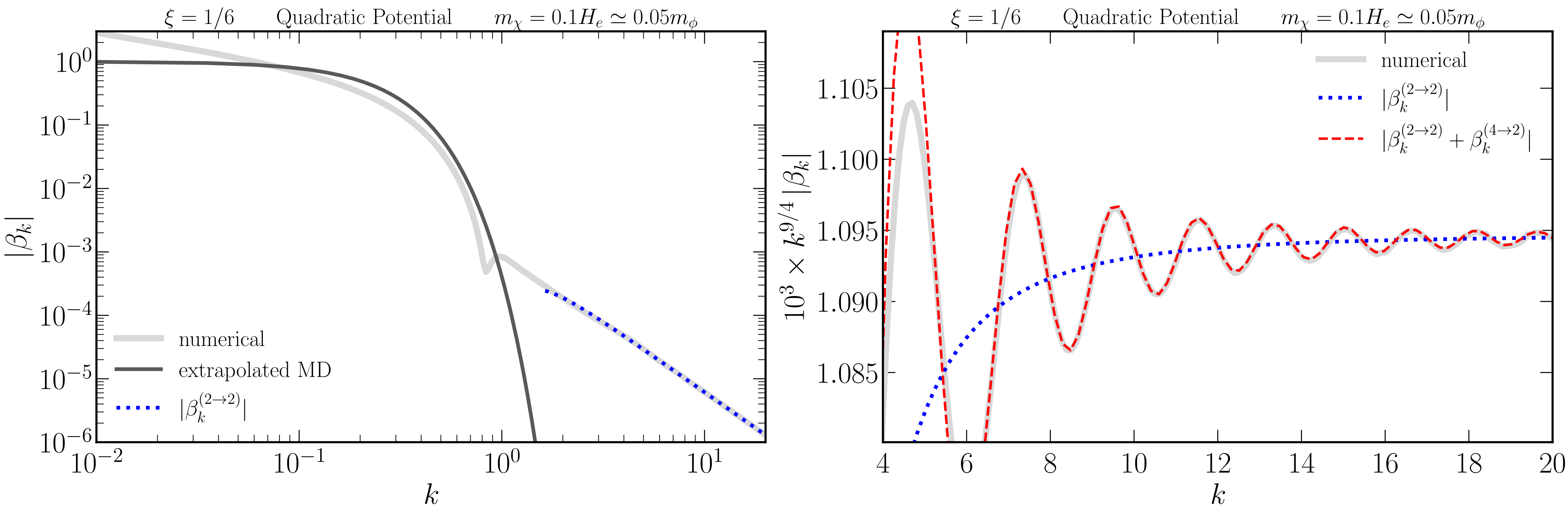


WTF? (Why These Features?) also, power-law decrease instead of exponential

We argue that these features are due to the quantum interference of coherent scattering reactions. We find analytic formulae for the particle production amplitude for a conformally-coupled scalar field, including an interference effect in the kinematic region where the production can be interpreted as inflaton scattering into scalar final states via graviton exchange.

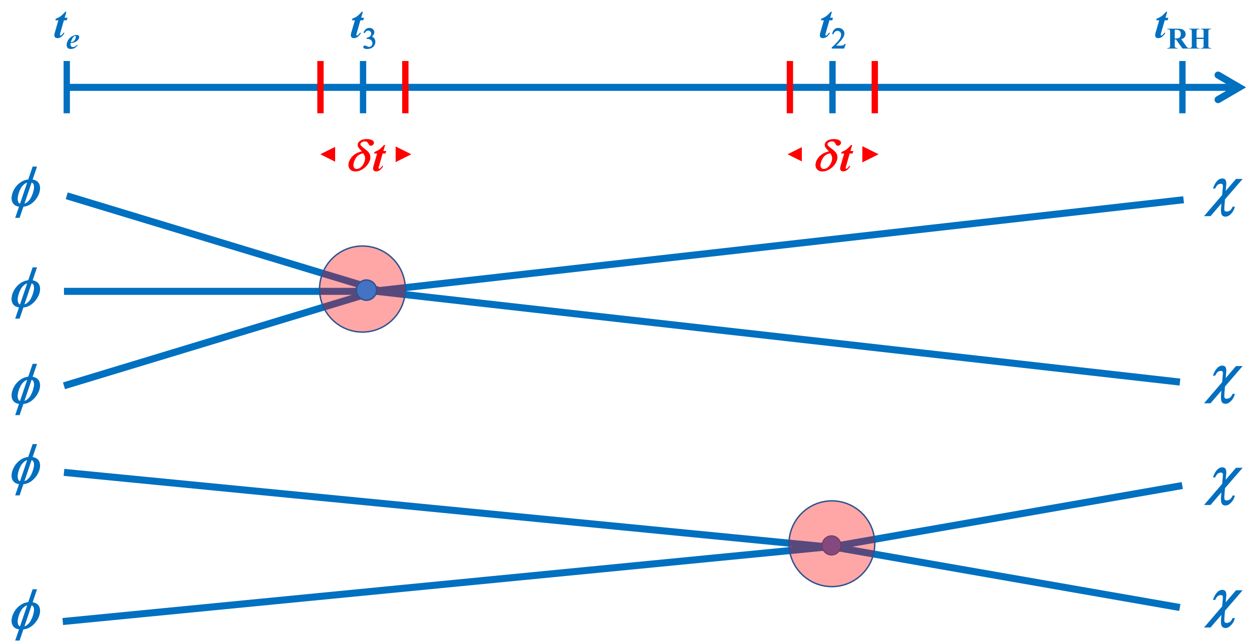
Inflaton Hilltop Potential



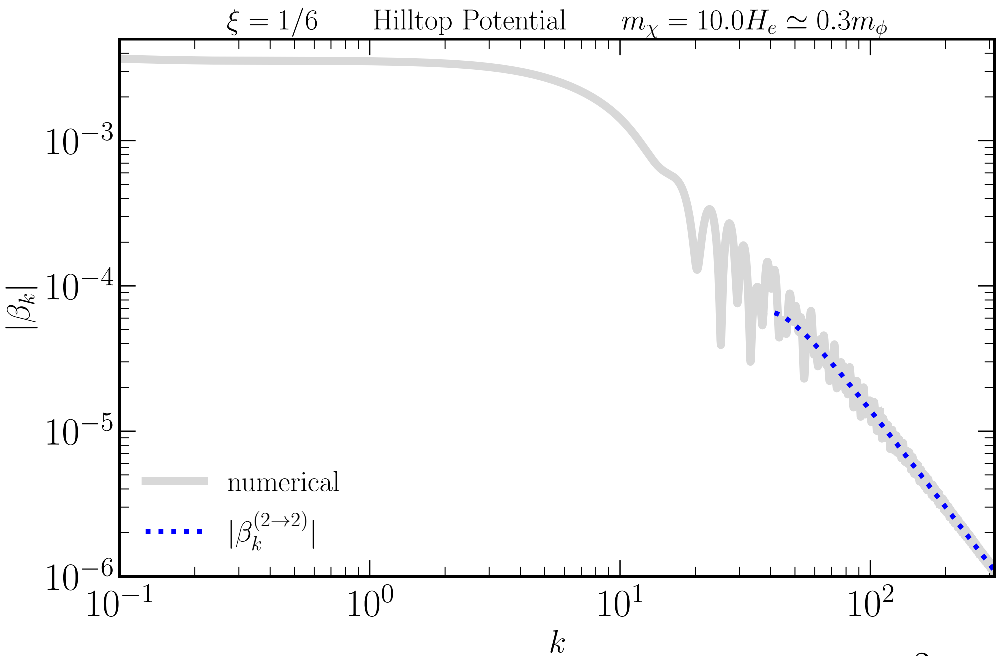


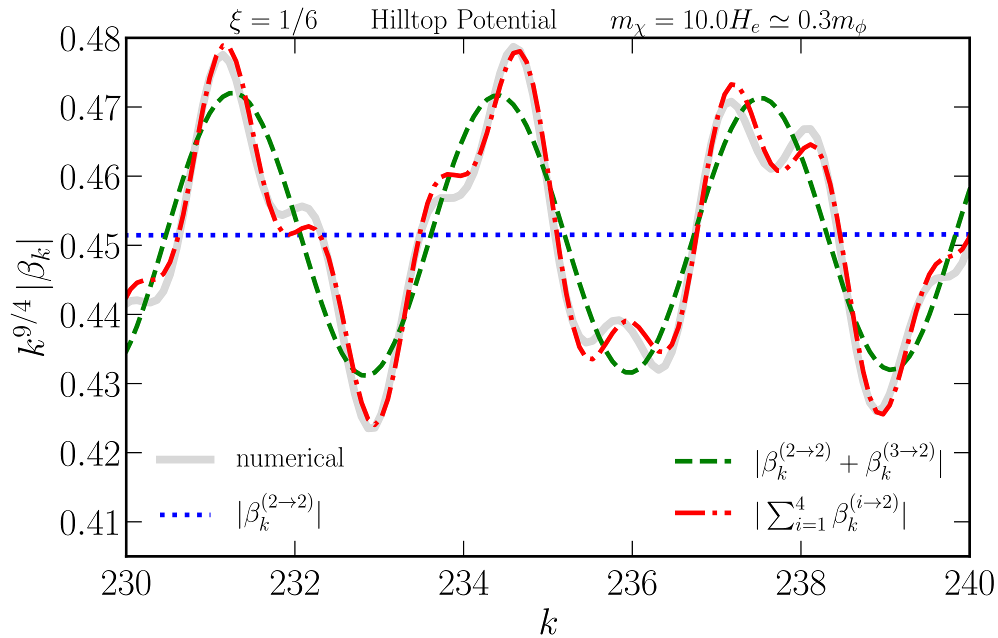
- Extrapolated MD (matter dominated-no inflaton oscillations) $|\beta_k| \propto \exp(-k^{3/2})$ for $k > 1$
- Numerical (quadratic inflaton potential with inflaton oscillations) $|\beta_k| \propto k^{-9/4}$ for $k > 1$
- Power-law behavior can be understood as $\phi + \phi \rightarrow \chi + \chi$ via a classical Boltzmann approach
- But, $\phi + \phi \rightarrow \chi + \chi$ via a classical Boltzmann approach cannot explain oscillations
- Oscillations due to quantum interference $|\, c_1 \langle \chi\chi | U | \phi\phi \rangle + c_2 \langle \chi\chi | U | \phi\phi\phi\phi \rangle \,|^2$

Quantum interference in gravitational particle production



- Initial macroscopic inflaton scattering state can be viewed as cold coherent superposition of $n\phi$ states
- Bogoliubov treatment allows processes that can be interpreted as $|\ c_1\langle\chi\chi|U|\phi\phi\rangle + c_2\langle\chi\chi|U|\phi\phi\phi\phi\rangle\ |^2$





- Hilltop inflaton potential $V \sim \left(1 - \frac{\phi^6}{v^6}\right)^2$ effective cubic term
- Quantum interference much more pronounced

A Question

What to make of a QFT that is "perfectly" reasonable in Minkowski,

but

Pathological in FLRW?

examples:
Fierz-Pauli (spin-2 with small mass)
Rarita-Schwinger (spin $3/2$ with small mass)

Finally, Summary: GPP can make DM & constrain BSM physics!

Dark matter might have only gravitational interactions (that's all we really "know")

If so, dark matter must have a gravitational origin.

Cosmological Gravitational Particle Production through Schrödinger's alarming phenomenon promising.

Scalars:

Conformally-coupled: promising DM candidate if $m \approx H_I$ (WIMPZILLA miracle).

Minimally-coupled: not promising DM candidate.

Late reheating: Ωh^2 much too large unless $m \gtrsim$ few H_I. Early reheating: Ωh^2 much too large unless $m \gtrsim$ few H_I.

Isocurvature constraints unless $m \gtrsim$ few H_I.

Dirac fermions:

Similar to conformally-coupled scalars: promising DM candidate if $m \approx H_I$ (WIMPZILLA miracle).

de Broglie—Proca vectors:

DM candidate could be very light ($\mu\mathrm{eV}$) or very massive (H_e)

Rarita-Schwinger fermions:

Catastrophic production if c_s vanishes. Implications for models of supergravity.

Fierz-Pauli tensors:

FRW-generalization of the Higuchi bound; DM relic abundance in progress.

Spin greater than 2: Alexander, Jenks, McDonough

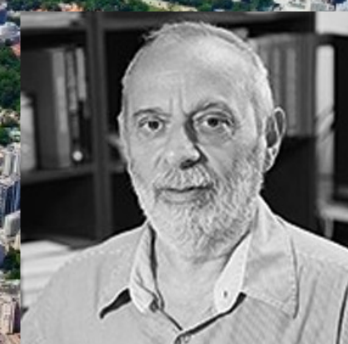
Coming soon to a Reviews of Modern Physics Near You

"Cosmological Gravitational Particle Production and its Implications for the Origin of Dark Matter"

With Andrew Long 2023

Gravitational Particle Production and Dark Matter — Four Lectures

1. Dark Matter: Evidence and the Standard WIMP
2. Gravitational Particle Production (Schrödinger's Alarming Phenomenon)
3. GPP of Scalar Fields
4. Beyond Scalar Fields



Rocky Kolb, University of Chicago

CBPF 9/2022