

Cosmological Gravitational Particle Production (CGPP)



Local Organising Committee

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Inner Space/Outer Space Interface

Particle physics (Inner Space) is
necessary to explain the universe

dark matter

dark energy

baryon asymmetry

CMB fluctuations

origin of structure

The universe (Outer Space) is
a particle physics laboratory

big bang as particle accelerator

limits on Beyond Standard Model physics

long lifetime/path length

stellar energy loss

large B fields

Inner Space/Outer Space Interface

Assumption: particle of interest was a component of the primordial soup
(present abundance determined by, e.g., freeze-out, freeze-in)

At some point $T > m$

Particle has SM interactions

BUT

Maximum temperature of the radiation-dominated universe is the “reheat” temperature after inflation, T_{RH}

T_{RH} may be as low as 8 MeV (to set stage for BBN)!

What about particles with no SM interactions (or) too weak to be populated in the primordial soup?

(No evidence that dark matter interacts with SM particles)

For 40 Years, Leading DM Candidate: “Weak”-Scale Cold Thermal Relic

- Mass: GeV – TeV
- “Weak-scale” interaction strength with SM (WIMP miracle)
- No self-interactions
- Produced by “freeze-out” from primordial plasma. COLD dark matter.
- “Detectable” by direct detection, indirect detection, decay products, production at colliders
- Just BSM, e.g., low-energy SUSY!

But WIMP stubbornly evaded detection!

What if DM interacts only gravitationally with SM?

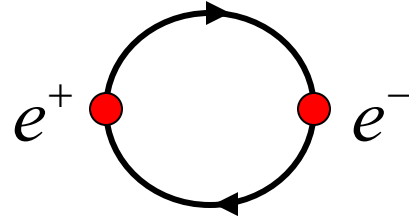
- Gravity must play a role in its cosmological production
- But gravity weak!

CGPP can be the origin of dark matter!

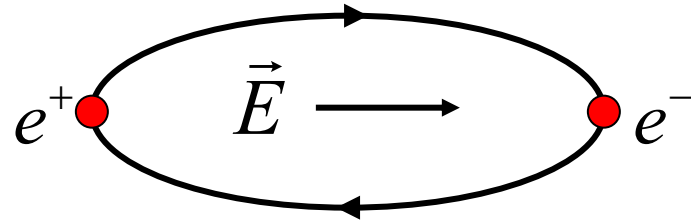
- CGPP is not optional! Can’t hide from gravity.

Disturbing the Quantum Vacuum

Electric Field \longrightarrow Particle creation



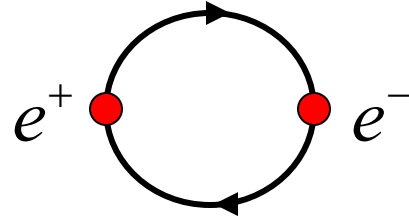
Particle creation if energy gained in acceleration from E -field over a Compton wavelength exceeds the particle's rest mass.



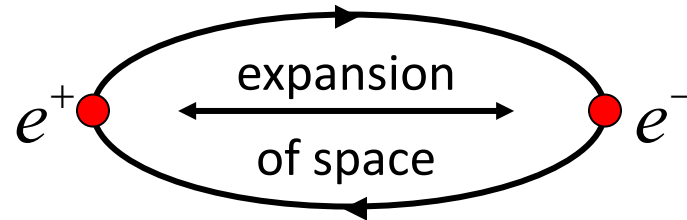
$$\left| \vec{E}_{\text{crit}} \right| = \frac{m_e^2 c^3}{e \hbar} \approx 10^{16} \text{ V cm}^{-1}$$

Disturbing the Quantum Vacuum

Expanding universe \longrightarrow Particle creation



Particle creation if energy gained in acceleration from expansion over a Compton wavelength exceeds the particle's rest mass.



$v = c$ at Hubble radius

$$H_{\text{crit}} = m$$

Scalar field in FLRW background

Covariant action for spectator scalar field (not the inflaton)

$$S[\varphi(x), g_{\mu\nu}(x)] = \int d^4x \sqrt{-g} \left[\frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi - \frac{1}{2} m^2 \varphi^2 + \frac{1}{2} \xi R \varphi^2 \right]$$

Gravity enters
the picture

ξ is a dimensionless constant: $\xi = 0$ minimal coupling; $\xi = 1/6$ conformal coupling.

But in principle ξ could be anything (and presumably there is RGE).

In spatially-flat FLRW background in conformal time: $dt = a d\eta$; rescaled field $\phi = a \varphi$

$$S[\phi(\eta, \mathbf{x})] = \int_{-\infty}^{\infty} d\eta \int d^3\mathbf{x} \left[\frac{1}{2} (\partial_\eta \phi)^2 - \frac{1}{2} (\nabla \phi)^2 - \frac{1}{2} m_{\text{eff}}^2 \phi^2 \right]$$

Time-dependent effective mass

$$m_{\text{eff}}^2(\eta) = a^2(\eta) \left[m^2 + \left(\frac{1}{6} - \xi \right) R(\eta) \right]$$

cosmological expansion \Rightarrow
time-dependent background field \Rightarrow
time-dependent Hamiltonian for spectator field

Scalar field in FLRW background

Fourier modes of ϕ obey wave equation: $\partial_\eta^2 \chi_k(\eta) + \omega_k^2 \chi_k(\eta) = 0$

Solutions to wave equation for mode functions include both + and – frequency terms

$$\chi_k(\eta) = \frac{\alpha_k(\eta)}{\sqrt{2\omega_k(\eta)}} e^{-i \int \omega_k(\eta) d\eta} - \frac{\beta_k(\eta)}{\sqrt{2\omega_k(\eta)}} e^{+i \int \omega_k(\eta) d\eta} \quad |\alpha_k|^2 - |\beta_k|^2 = 1$$

If start with only positive frequency modes, $|\alpha_k| = 1$ & $|\beta_k| = 0$,

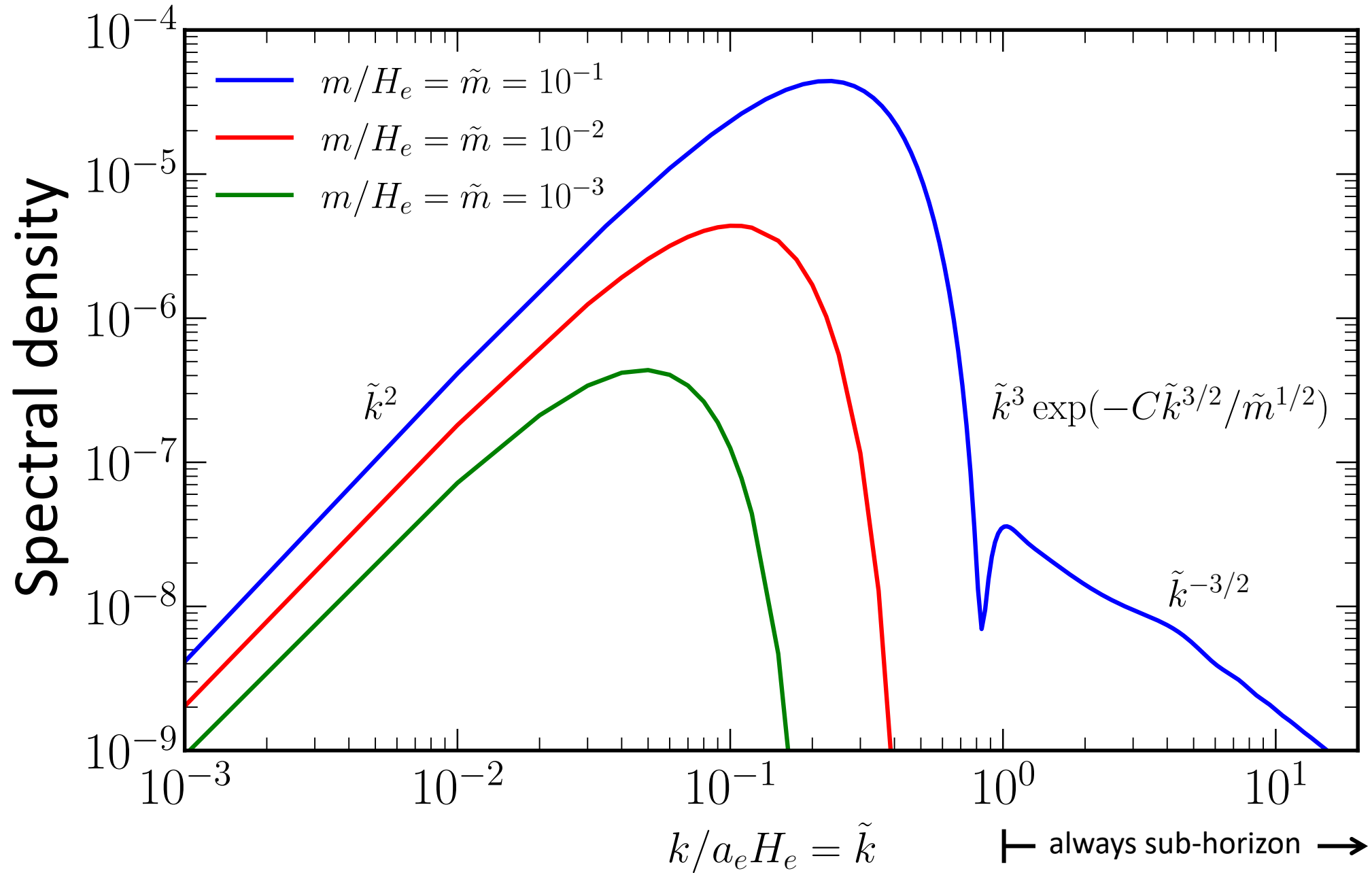
Expansion of the universe will generate negative frequency modes (particles), $\beta_k \neq 0$.

Comoving number density of particles at late time is

$$a^3 n = \int \frac{dk}{k} \underbrace{\frac{k^3}{2\pi^2} |\beta_k|^2}_{n_k = \text{spectral density}}$$

$n_k = \text{spectral density}$

Quadratic Inflaton Potential for Conformally-Coupled Scalar: $\xi = 1/6$

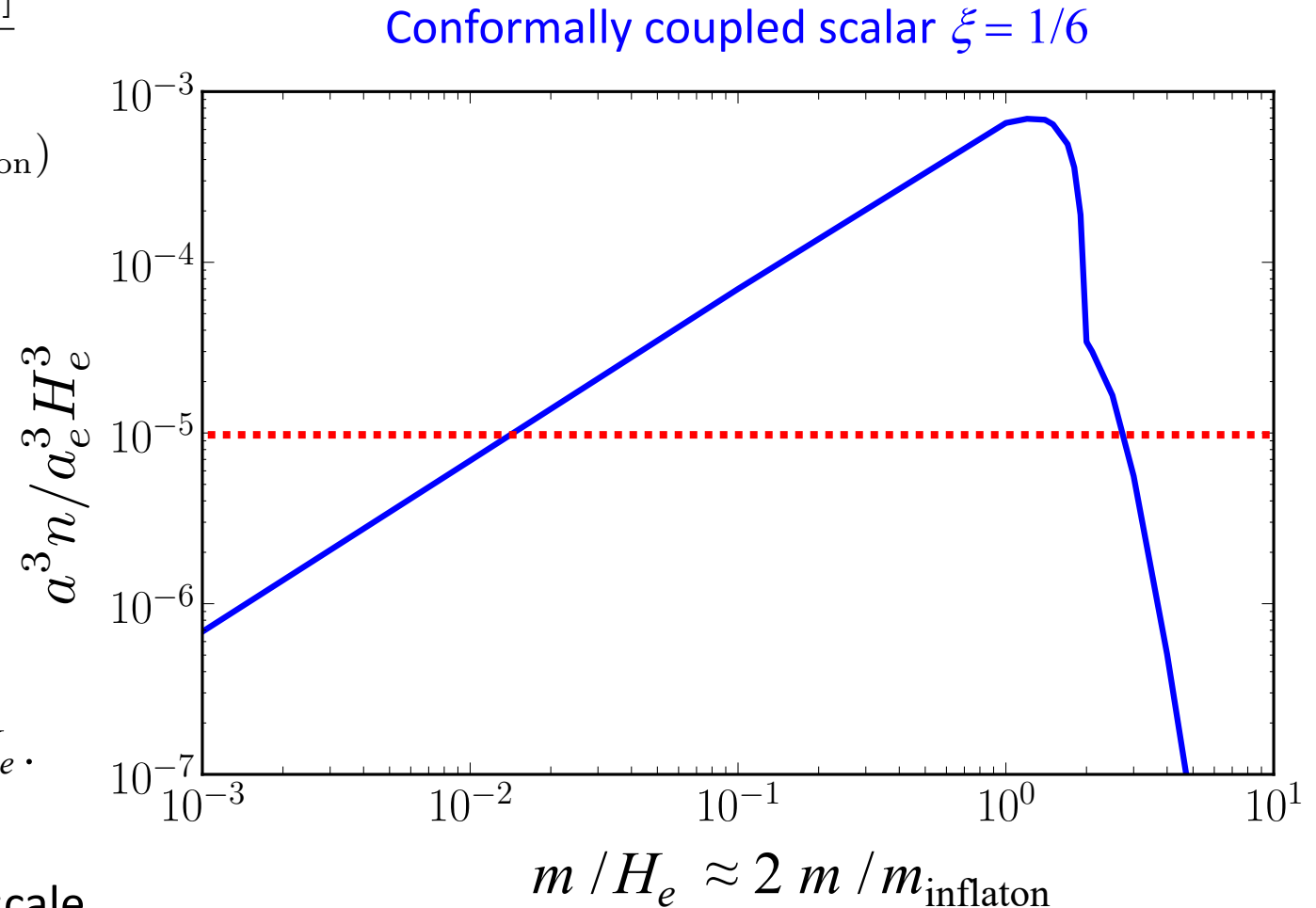


Quadratic Inflaton Potential for Conformally-Coupled Scalar: $\xi = 1/6$

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

$$\sim \left(\frac{m}{10^{11} \text{GeV}} \right)^2 \left(\frac{T_{\text{RH}}}{10^9 \text{GeV}} \right) \quad (m \lesssim m_{\text{inflaton}})$$

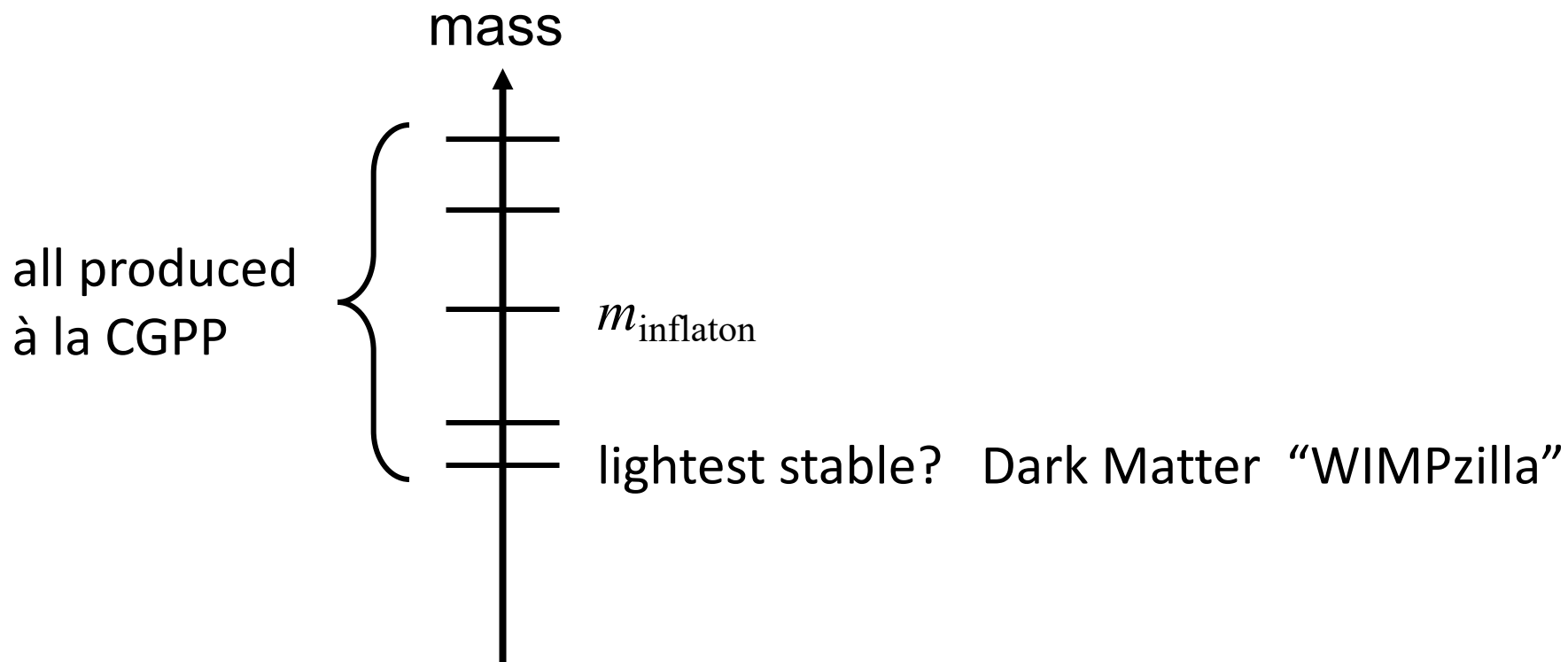
- Calculation assumes inflationary model (quadratic, which is ruled out).
- But general picture holds in other models since action occurs around end of inflation.
- Don't know, but $H_e \approx 10^{11} \text{ GeV}$ and $T_{\text{RH}} \approx 10^9 \text{ GeV}$ are "common."
- If stable and dark matter, $\Omega h^2 = 0.12 \Rightarrow m \approx H_e$.
Could have been anything! WIMPZILLA miracle!
- Perhaps inflation scale represents new physics scale, stable particle at that mass scale natural DM candidate.



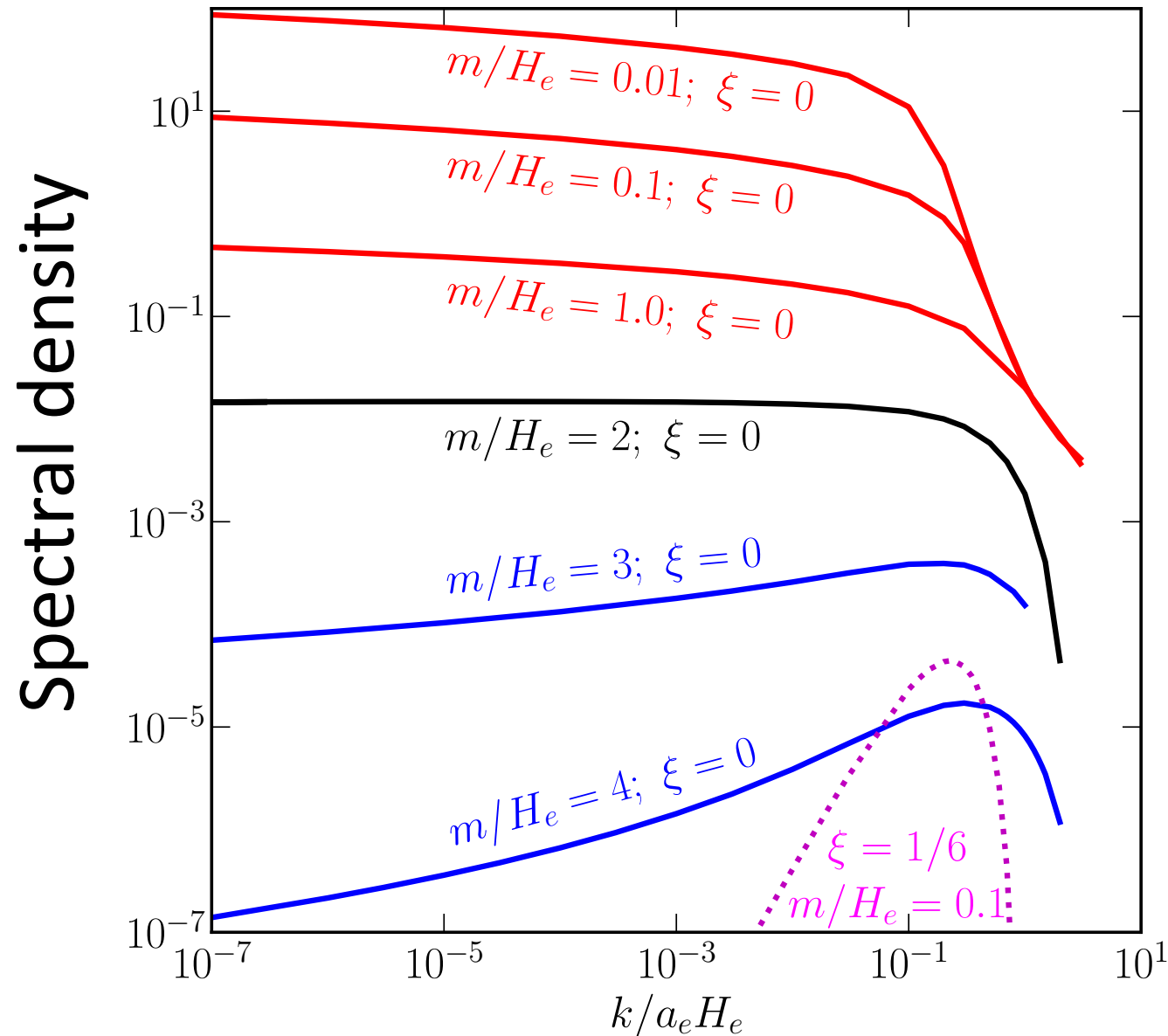
Conformally-coupled scalar WIMPZILLA DM candidate
if $m_\chi = \mathcal{O}(m_{\text{inflaton}})$

GPP & Dark Matter

- Inflation indicates a new mass scale
- In most models, $m_{\text{inflaton}} \approx H_{\text{inflation}} \approx 10^{12} - 10^{14} \text{ GeV}$?
- $H_{\text{inflation}}$ detectable via primordial gravitational waves in CMB
- (I, at least) expect other particles with mass $\approx m_{\text{inflaton}}$



Quadratic Inflaton Potential for Minimally-Coupled Scalar: $\xi = 0$



Red Spectrum leads to dangerous isocurvature fluctuations

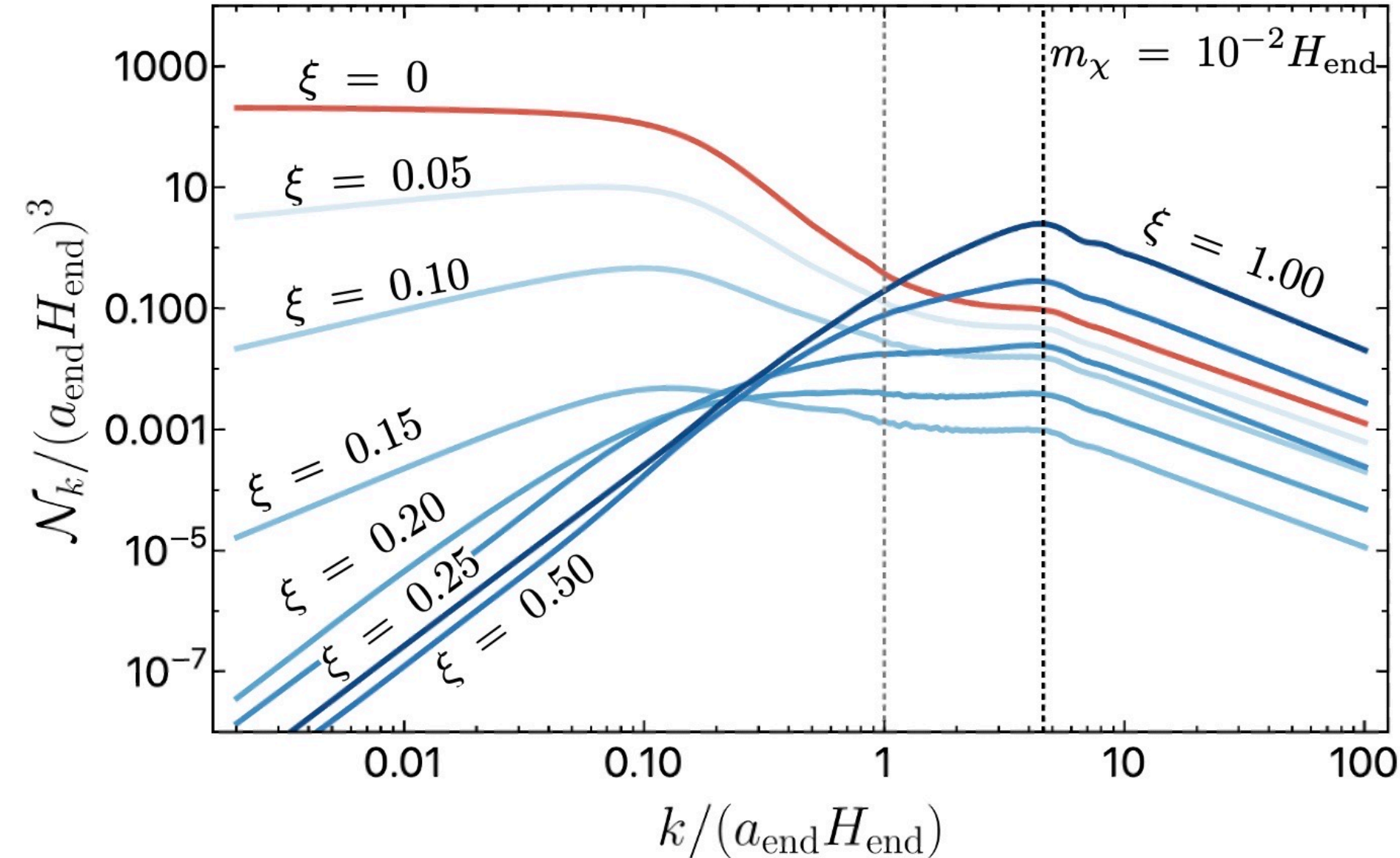
CMB limits

Chung, EWK, Riotto, Senatore (05)

Stable, minimally-coupled scalars are disallowed if $m \lesssim \text{few } H_e$

Model-T inflation model (Kallosh & Linde): $V(\varphi) = 10^{-10} M_{\text{Pl}}^4 \tanh(\varphi/\sqrt{6}M_{\text{Pl}})$

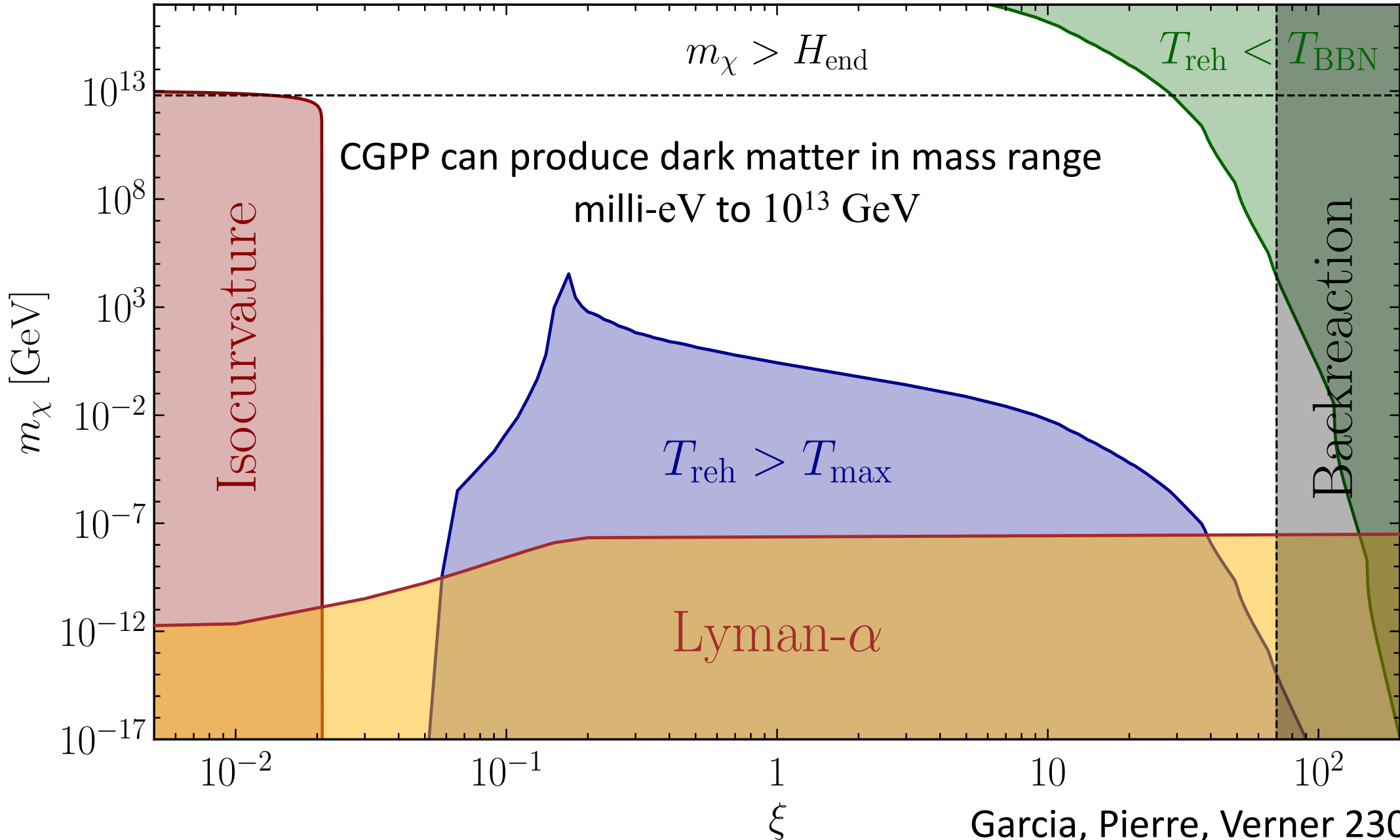
$$m_{\text{eff}}^2 = m^2 + \frac{1}{6}(1 - 6\xi)R$$



Garcia, Pierre, Verner
2305.14446

also EWK, Long, McDonough,
Payeur 2211.14323

Model-T inflation model (Kallosh & Linde): $V(\varphi) = 10^{-10} M_{\text{Pl}}^4 \tanh(\varphi/\sqrt{6} M_{\text{Pl}})$



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

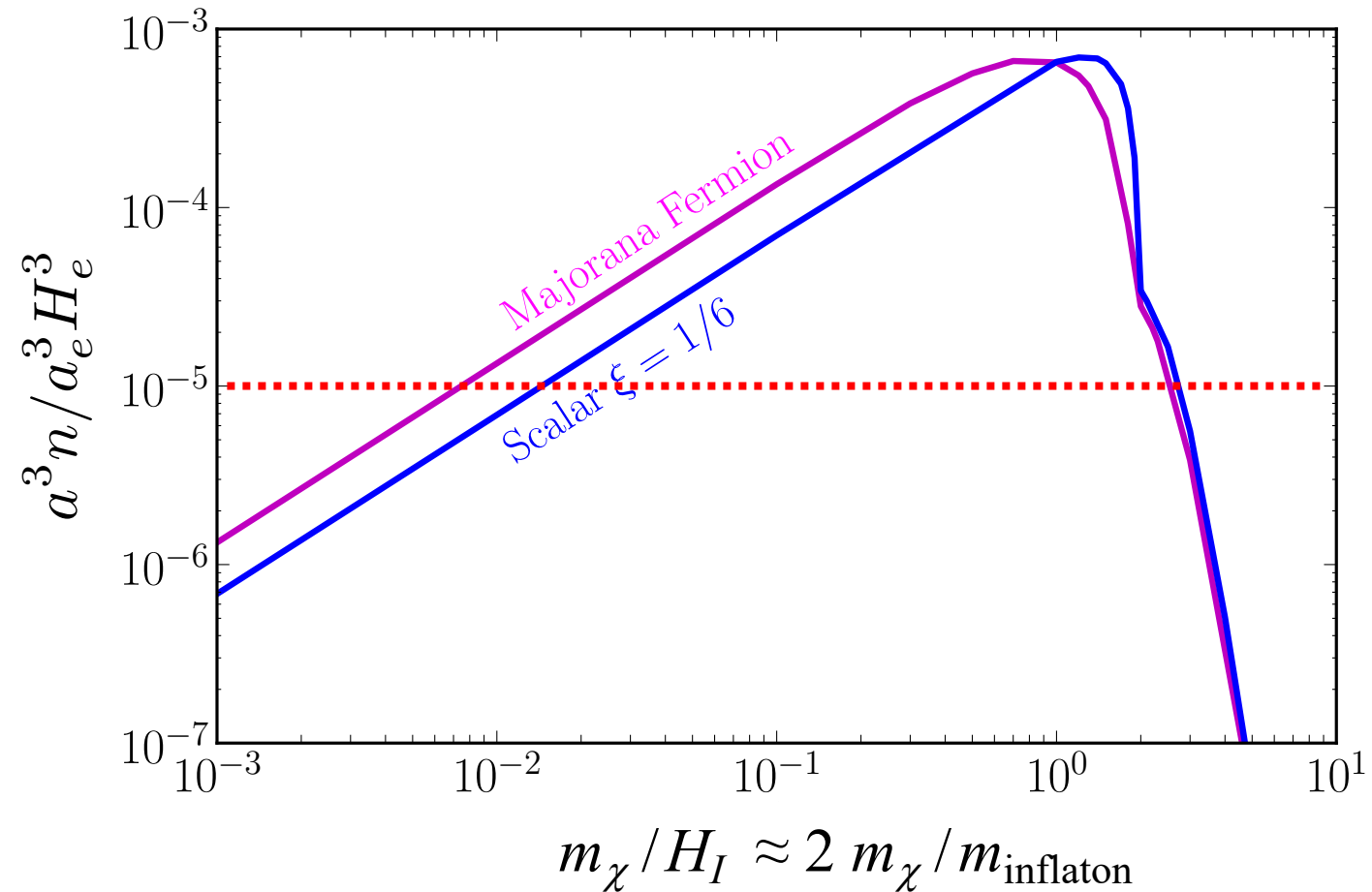
Adiabaticity parameter
 $k/m \times$ conformal scalar

Blue spectrum: no isocurvature issues

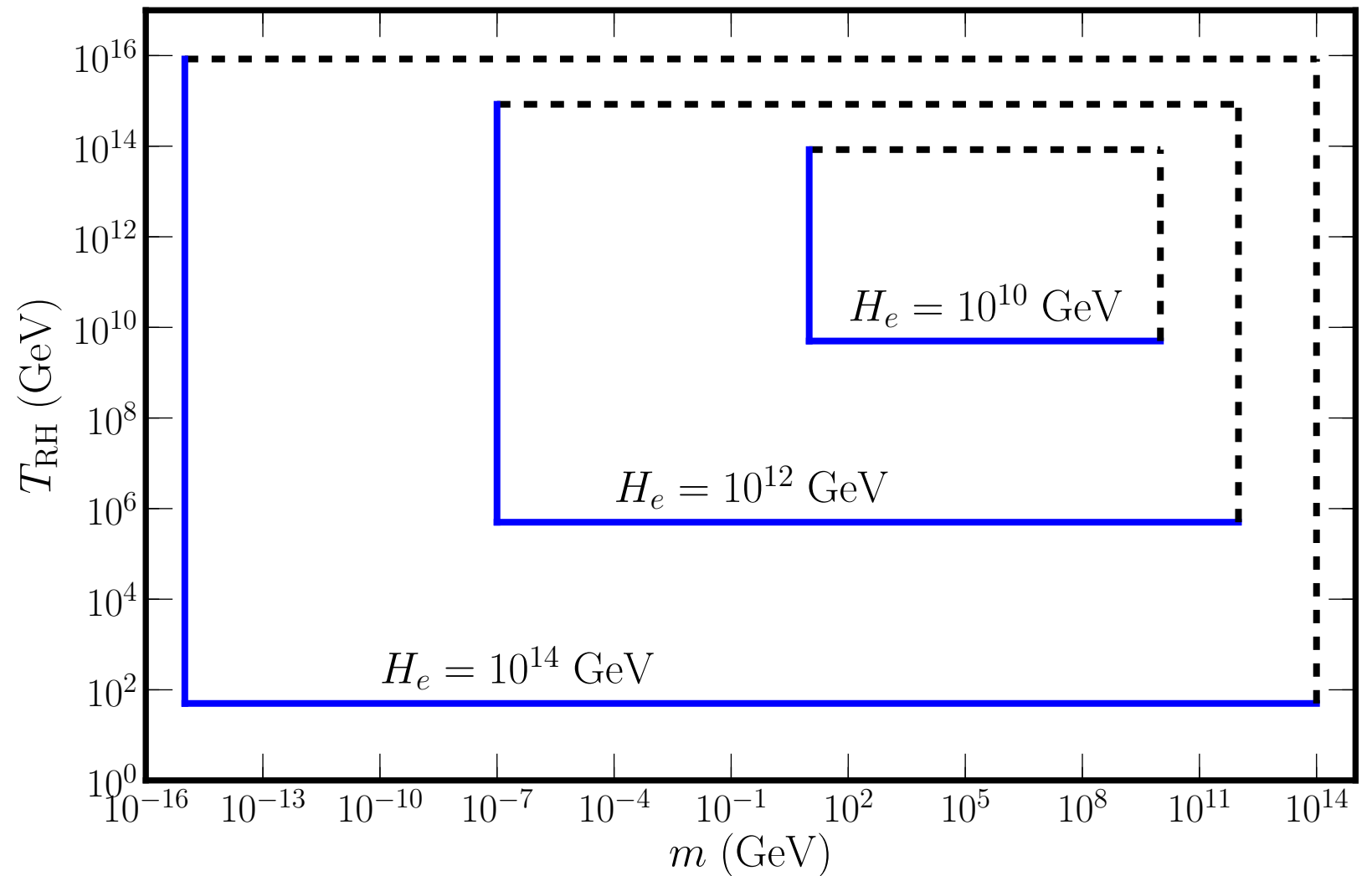
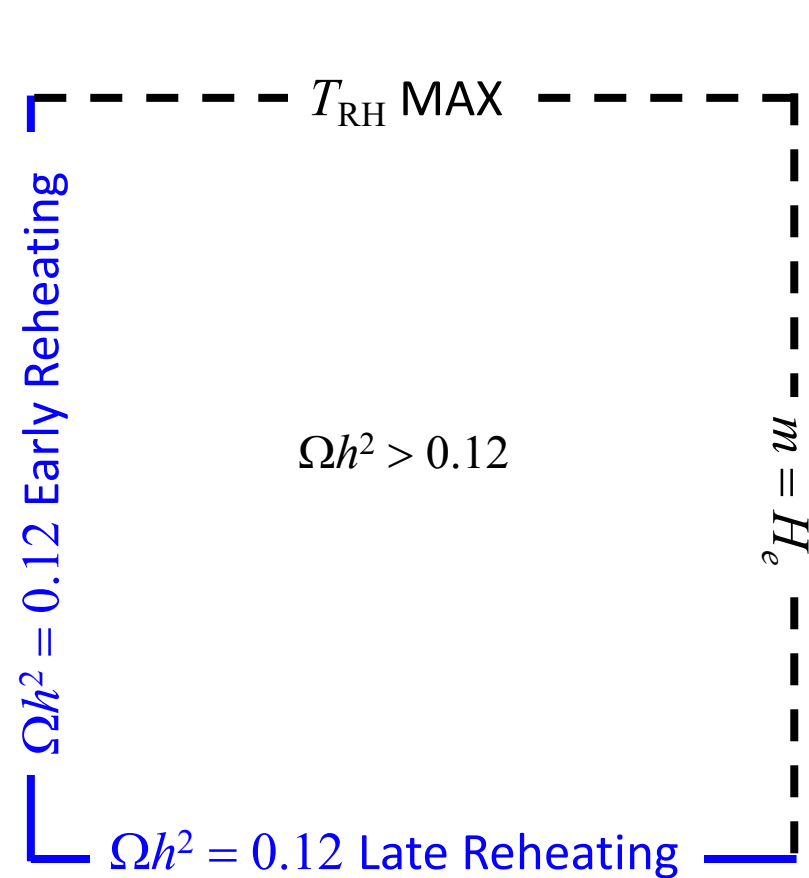
Dirac WIMPZILLA DM candidate for
 $m = \mathcal{O}(m_{\text{inflaton}})$

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

$$\sim \left(\frac{m}{10^{11} \text{GeV}} \right)^2 \left(\frac{T_{\text{RH}}}{10^9 \text{GeV}} \right) \quad (m \lesssim m_{\text{inflaton}})$$



de Broglie—Proca field in FLRW background



Early/Late:

$$T_{\text{RH}} = 8.4 \times 10^8 \left(\frac{m}{\text{GeV}} \right)^{1/2} \text{ GeV}$$

Very light (μeV) DM from GPP

Graham, Mardon, & Rajendran

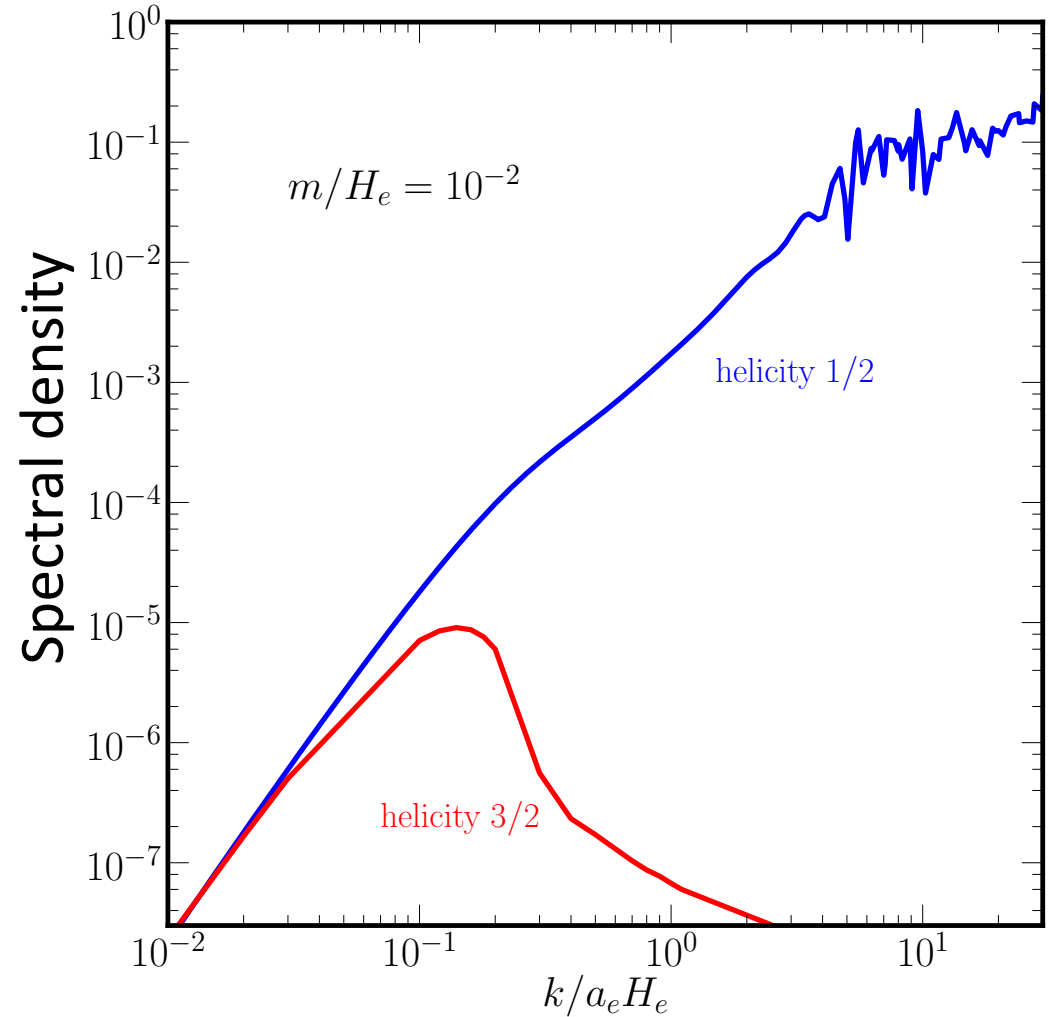
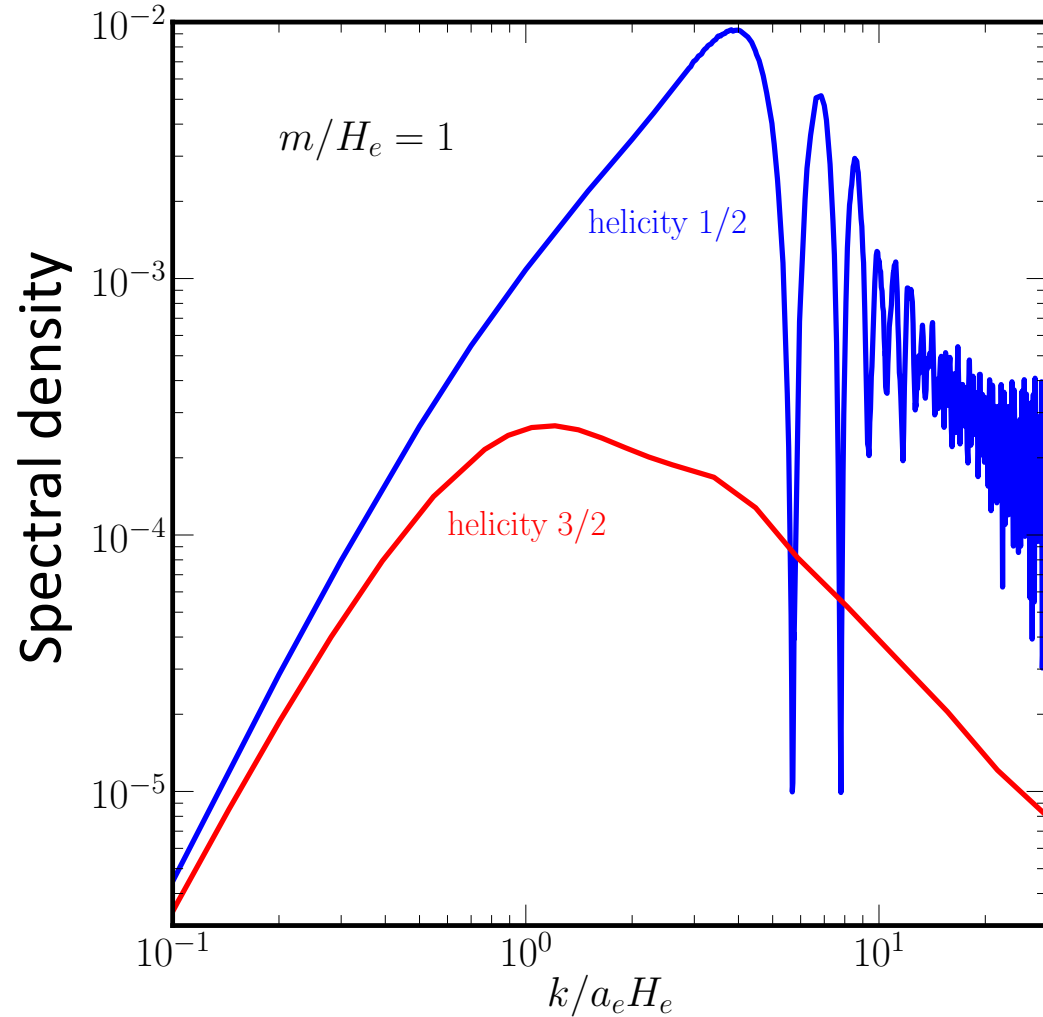
or

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

Ahmed, Grzadkowski, & Socha
EWK & Long

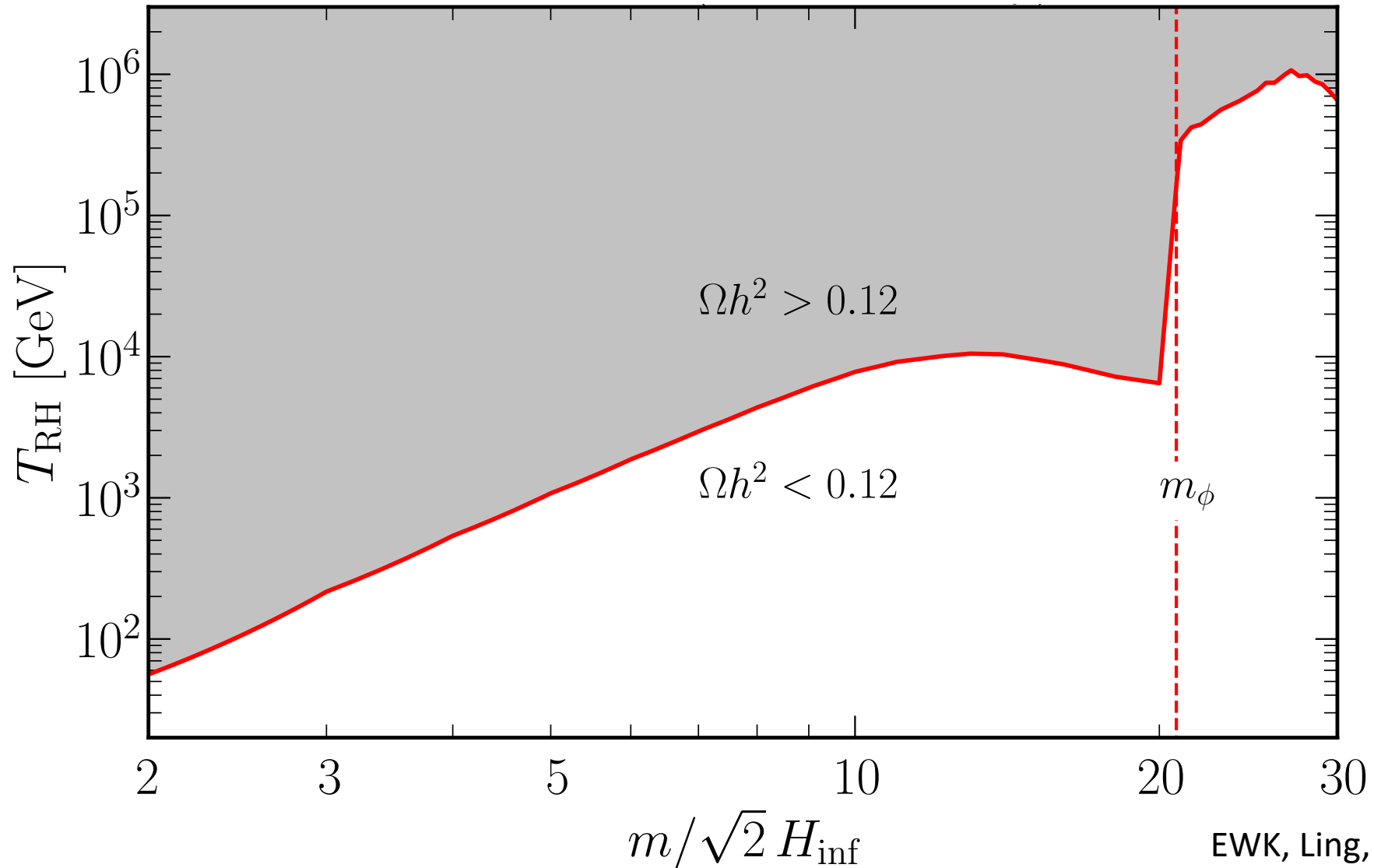
Rarita-Schwinger field in FLRW background

Catastrophic production for low-mass ($m < H_e$) due to vanishing sound speed



Massive Bigravity

Theory (ghost-free in Minkowski) propagates ghost in FLRW for low-mass, $m^2 < 2H_e^2 (1-\varepsilon)$



Representation	Particle	1-point function Dark Matter	2-point function CMB Isocurvature	3-point function CMB Nongaussian
(0,0)	Conformally Coupled Scalar $\xi = 1/6$	Kuzmin & Tkachev (99)	Expected to be very small (blue)	Chung & Yoo (13)
(0,0)	Minimally Coupled Scalar $\xi = 0$ (e.g., inflaton)	Kuzmin & Tkachev (99)	Chung, EWK, Riotto, & Senatore (05)	
$(1/2,0) \oplus (0,1/2)$	“Dirac” Fermion	Chung, EWK, & Riotto (98)	Expected to be very small (blue)	
$(1/2,1/2)$	de Broglie-Proca Vector	Graham & Mardon (16); Ahmed, Grzadkowski,& Socha (20); EWK & Long (21)		
$(1,0) \oplus (0,1)$	2-Form (Pseudo) Vector (e.g., Kalb-Ramond)	Capanelli, Jenks, EWK, & McDonough (in prep.)		
$(1/2,1) \oplus (1,1/2)$	Rarita-Schwinger Fermion (e.g., gravitino)	EWK, Long, & McDonough (21)		
$(1,1)$	Fierz-Pauli (massive graviton)	EWK, Liang, Long, Rosen (23)		
Higher-spin bosons		Jenks, Koutrolikos, McDonough, Alexander, Gates (23)		

Finally, Summary: **CGPP can produce 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 promising.

Scalars:

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

Minimally-coupled: not promising DM candidate, exclude stable particles with $m \lesssim \text{few } H_e$.

If allow $2 \times 10^{-2} \lesssim \xi \lesssim 10^2$ DM candidate in mass range milli-eV to 10^{13} GeV.

Dirac fermions:

Like conformally-coupled scalars; promising DM candidate if $m \approx H_e$ (WIMPZILLA miracle).

de Broglie—Proca vectors:

DM candidate could be very light (μeV) or very massive (H_e).

Rarita-Schwinger fermions:

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

Gravitinos: EWK, Long, McDonough (2021); Dudas, Garcia, Mambrini, Olive, Peloso, Verner (2021)

Fierz-Pauli tensors:

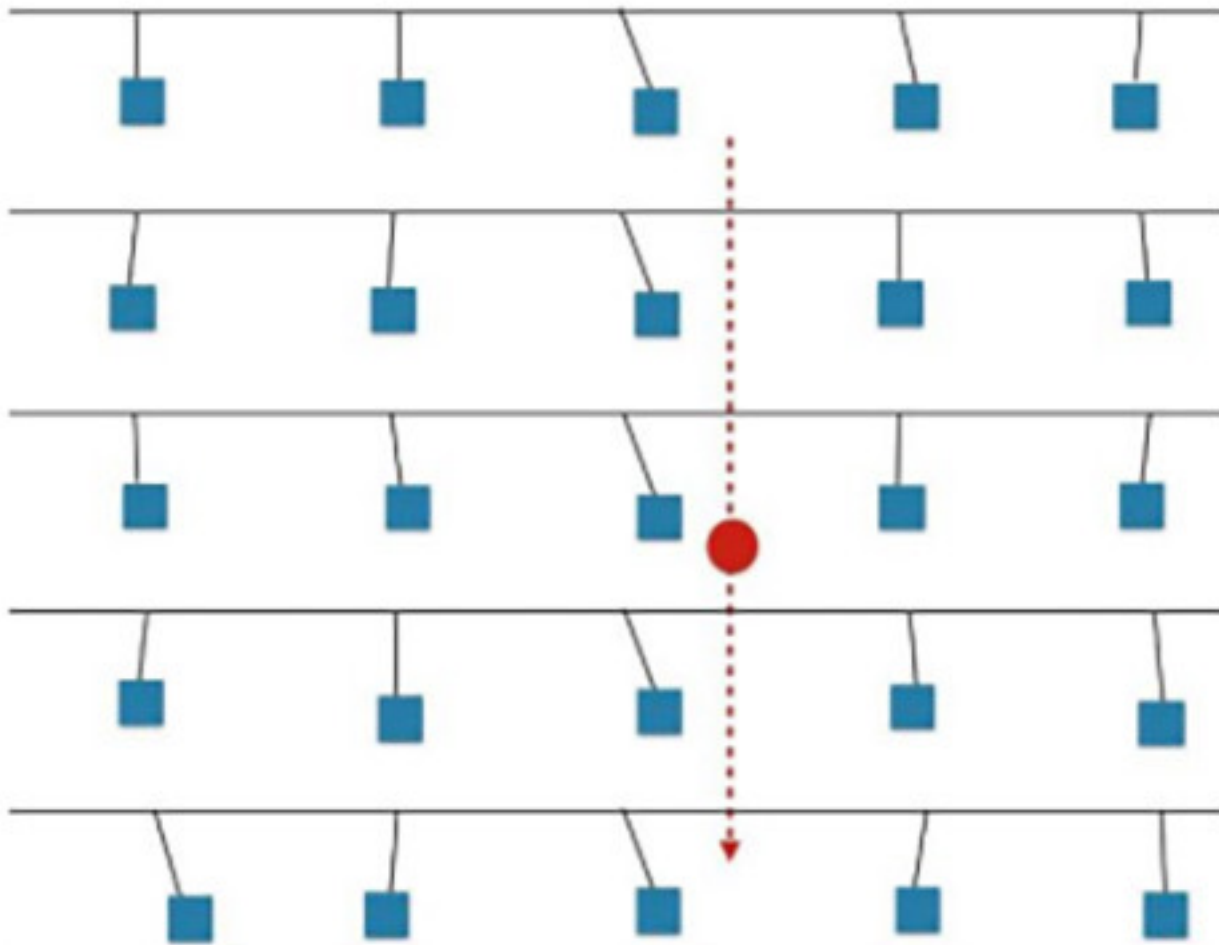
FRW-generalization of the Higuchi bound; DM relic abundance.

Spin greater than 2: Jenks, Koutrolikos, McDonough, Alexander, Gates

Windchime: Detect WIMPzillas with only gravitational coupling

“Gravitational Direct Detection of Dark Matter” Carney, Ghosh, Krnjaic, Taylor arXiv: 1903.00492

Windchime



$$\text{SNR}^2 = 10^4 \left(\frac{M_\chi}{1 \text{ mg}} \right)^2 \left(\frac{M_D}{1 \text{ mg}} \right)^2 \left(\frac{1 \text{ mm}}{d} \right)^4$$

Meter-scale detector

Billion microgram to milligram sensors

Lattice spacing millimeter to centimeter

Detect DM of mass greater than Planck mass

How about 10^{-6} Planck mass?

Much Recent Work ... Many Open Roads

- Complete CGPP for higher-spin fields
- Fully explore Rarita-Schwinger = Gravitino
- Massive particles from K-K reduction in SUGRA/Strings
- Understand what it means to have ghosts
- Develop CMB implications
- Dark matter as Kalb-Ramond field?
- Long-lived massive particles from CGPP
 - Baryo/leptogenesis?
 -
- Direct detection?

Coming soon-ish, to a *Reviews of Modern Physics* Near You

Cosmological gravitational particle production and its implications for cosmological relics

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The focus of this review is the phenomenon of particle production in the early universe solely by the expansion of the universe, with particular attention to the possibility that the created particle species could be the dark matter. We will treat particle production by cosmological expansion for particles of spin 0, 1/2, 1, 3/2, and 2, and comment on the possibility of larger spins. For the early-universe evolution of the background spacetime we assume an initial inflationary phase, followed by a transition to a matter-dominated phase, eventually transiting to a radiation-dominated phase. We review the two basic requirements for particle production by the expansion of the universe: 1) the contribution to the matter action from the particle must violate conformal invariance (the trace of the matter stress-energy tensor involving the new field must be nonzero), and 2) the mass of the particle must not be too much in excess of the expansion rate of the universe during inflation. In this review we specialize to a Friedman-Lemaître-Robertson-Walker cosmological model, and calculate the spectrum of particles resulting from the expansion of the universe. We summarize the criteria for the resulting density of particles to be sufficient to account for the dark matter, as well as discuss several other cosmological implications. We then mention other mechanisms for cosmological particle production through gravity: particle production from the standard-model plasma through graviton exchange, particle production through black-hole evaporation, and particle production through a misalignment mechanism.

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July 2023

Thanks to my collaborators in 25 years of CGPP: (Chung, EWK, Riotto, *PRD* **59** (1998) 023501)

Ivone Albuquerque, Edward Basso, Christian Capanelli, Daniel Chung, Patrick Crotty,
Michael Fedderke, Gian Giudice, Lam Hui, Leah Jenks, Siyang Lin, Andrew Long,
Evan McDonough, Toni Riotto, Rachel Rosen, Leo Senatore, Alexi Starobinski,
Igor Tkachev, Mark Wyman

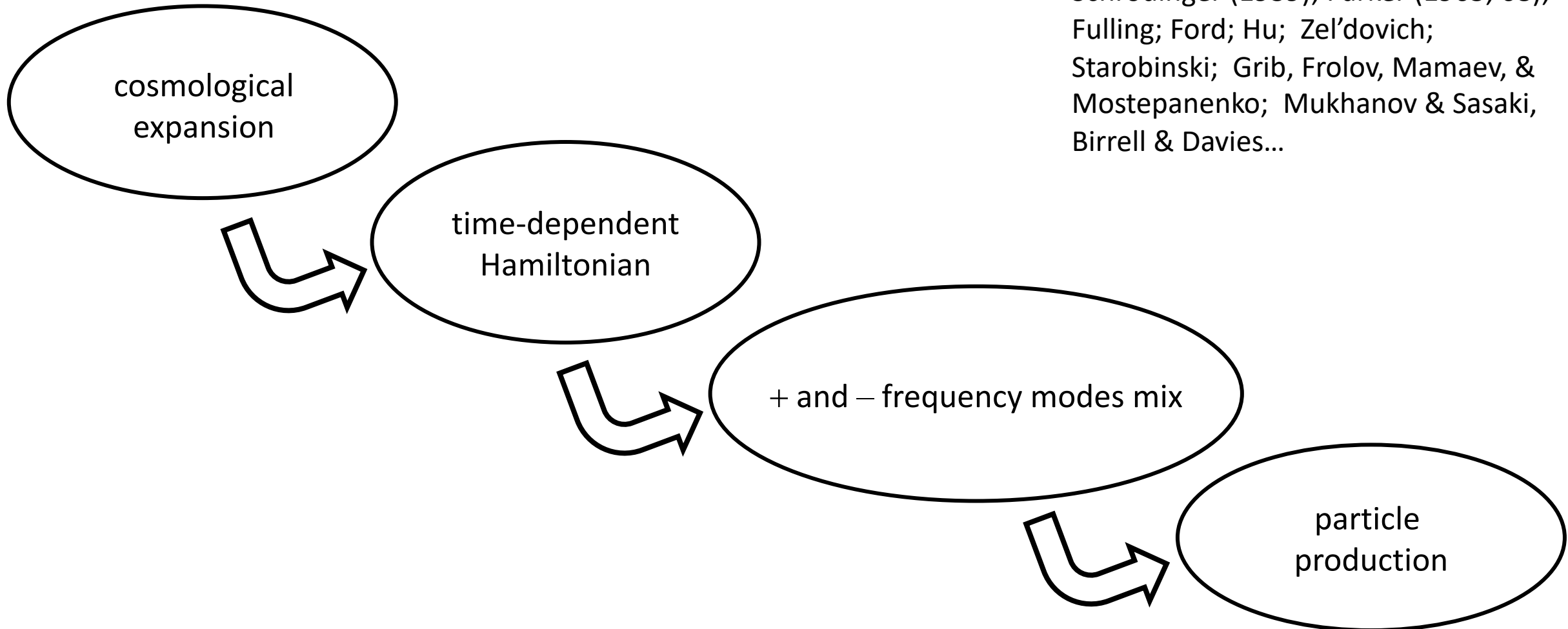
Cosmological Gravitational Particle Production (CGPP)

- An external field can create particles from the vacuum
 - Expanding Universe – Schrödinger 1939
 - Electric Fields – Schwinger 1951
 - Black Holes – Hawking 1974
- I will consider time-dependent gravitational fields, in particular, the big bang
 - Inflation: Quasi deSitter (QdS) phase followed by transition to matter-dominated (MD) then radiation-dominated (RD) phase
- CGPP is an exercise of QFT in classical gravitation background. Many interesting facets, but ...
- ... my motivation is to explore whether GPP can be the origin of **DARK MATTER** (DM) and whether can provide cosmological constraints on **BSM** physics
- CGPP is **not optional!**

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.

In the early days:
Schrodinger (1939); Parker (1965, 68);
Fulling; Ford; Hu; Zel’dovich;
Starobinski; Grib, Frolov, Mamaev, &
Mostepanenko; Mukhanov & Sasaki,
Birrell & Davies...



Fields with Spin $> 1/2$

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

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