Rarita-Schwinger Fields and Cosmology

Sep 22 – 25, 2025

University of Warsaw, Faculty of Physics

KICP

Rocky Kolb

THE UNIVERSITY OF CHICAGO

Inner Space/Outer Space Interface

Cosmological limits on particle properties:

1. neutrinos
2. axions
3. magnetic monopoles
4. all sorts of BSM particles (e.g., SUSY)
5. cosmological defects
6. Kaluza-Klein modes
7. String theorists suggest a lot of unseen things … difficult to get rid of them

Usually assume LTE

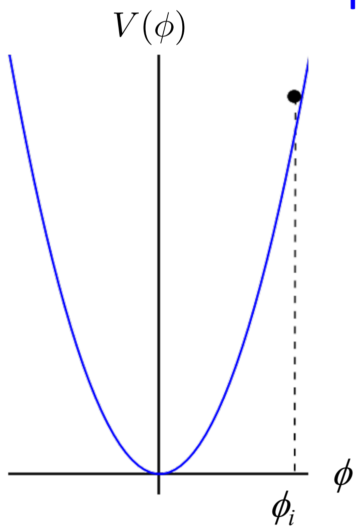
I will consider limits from "cosmological gravitational particle production (CGPP)"

CGPP can populate hidden sectors & produce DM w/ only gravitational interactions

Image credit: Chris Stabb

Ideas for gravitational particle production

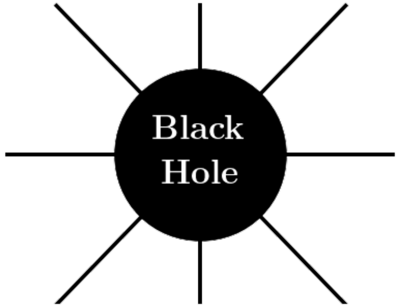
Misalignment



- Superhorizon quantum fluctuations during inflation
- After inflation, field frozen by "Hubble drag" until H drops below mass
- Then energy density in oscillating field
- Most familiar example is the axion

Hawking radiation from primordial black holes

Hooper, Krnjaic, & McDermott



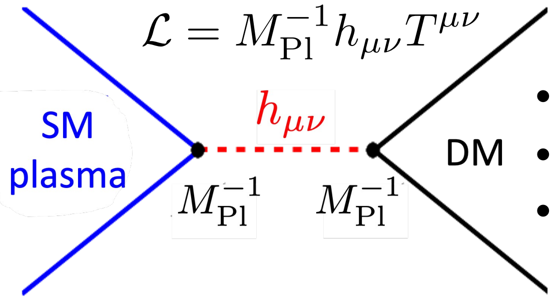
$$\frac{\Omega h^2}{0.12} \approx \left(\frac{10^{11}\mathrm{GeV}}{m}\right)\left(\frac{10^{12}\mathrm{GeV}}{T_i}\right)^3\left(\frac{\epsilon_{\mathrm{BH}}}{10^{-16}}\right)$$

- PBH seeds from inflation
- PBHs evaporate in early universe
- DM mass $\sim 10^{11}\,\mathrm{GeV}$ (WIMPzilla)

From primordial plasma via graviton exchange

Garny, Sandora, & Sloth

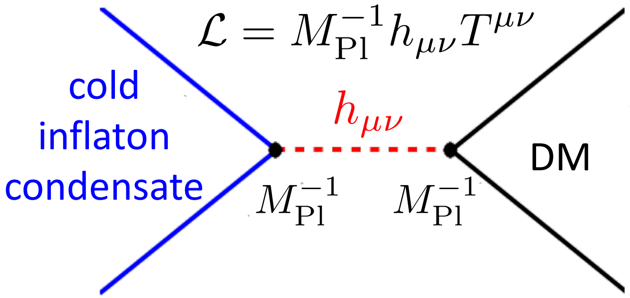
$$\frac{\Omega h^2}{0.12} \approx \left(\frac{\langle\sigma v\rangle}{T^2/M_{\mathrm{Pl}}^4}\right)\left(\frac{m}{10^{13}\mathrm{GeV}}\right)\left(\frac{T_{\mathrm{RH}}}{10^{14}\mathrm{GeV}}\right)^3$$



- Reheating produces SM plasma
- DM mass $\sim 10^{13}\,\mathrm{GeV}$ (WIMPzilla)
- Assumes $m < T_{\mathrm{RH}}$

From inflaton field after inflation via graviton exchange

Ema, Nakayama, Tang; Mambrini & Olive



- "Boltzmann" approach not complete treatment (Kaneta, Lee, Oda; Basso, Chung, EWK, Long).
- Underestimates particle production: must include Schrödinger Effect (production during quasi-de Sitter era).

Ideas for gravitational particle production

Cosmological Gravitational Particle Production (CGPP) through the Schrödinger Effect

Physica VI, no 9 October 1939

THE PROPER VIBRATIONS OF THE EXPANDING UNIVERSE

by ERWIN SCHRÖDINGER

§ 1. *Introduction and summary*. Wave mechanics imposes an a priori reason for assuming space to be closed; for then and only then are its proper modes discontinuous and provide an adequate description of the observed atomicity of matter and light. — Einsteins theory of gravitation imposes an a priori reason for assuming space to be, if closed, expanding or contracting; for this theory does not admit of a stable static solution. — The observed facts are, to say

These are the broad results. A finer and particularly interesting phenomenon is the following.

The decomposition of an arbitrary wave function into proper vibrations is rigorous, as far as the functions of space (amplitude-functions) are concerned, which, by the way, are exactly the same as in the static universe. But it is known, that, with the latter, two frequencies, equal but of opposite sign, belong to every space function. *These two* proper vibrations cannot be rigorously separated in the expanding universe. That means to say, that if in a certain moment only one of them is present, the other one can turn up in the course of time.

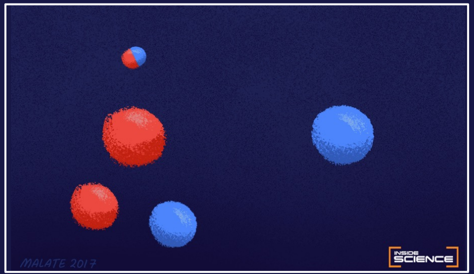
Generally speaking this is a phenomenon of outstanding importance. With particles it would mean production or anihilation of matter, merely by the expansion, whereas with light there would be a production of light travelling in the opposite direction, thus a sort of reflexion of light in homogeneous space. Alarmed by these prospects, I have investigated the question in more detail. Fortunately the equations admit of a solution by familiar functions, if R is a *linear* function of time. It turns out, that in this case the alarming

Physics of "Schrödinger Effect" in the spirit of the "Schwinger Effect"

The Schwinger Effect

Electric field $\longrightarrow$ Particle creation

Quantum Vacuum



Seething Sea of Uncertainty

Image: Malate 2017 (AIP)

Turn on $\vec{E}$ field

$$\longleftarrow \quad \vec{E} \quad \longrightarrow$$

Particle creation from the vacuum if energy gained in acceleration from $\vec{E}$ field over a Compton wavelength exceeds the particle's rest mass.

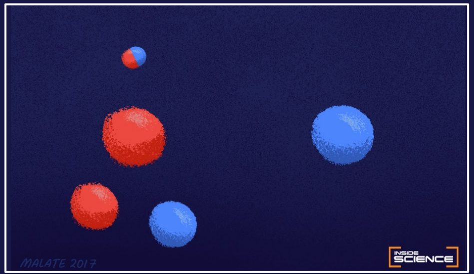
$$\left|\vec{E}_{\mathrm{crit}}\right| = \frac{m_e^2 c^3}{e\hbar} \approx 10^{16}\ \mathrm{V\ cm^{-1}} \Longrightarrow \Gamma \propto e^{-\left|\vec{E}_{\mathrm{crit}}\right|/\left|\vec{E}\right|}$$

Sauter (1931); Heisenberg & Euler (1935); Weisskopf (1936); Schwinger (1951)

The Schrödinger Effect

Expanding space $\longrightarrow$ Particle creation

Quantum Vacuum



Seething Sea of Uncertainty

Image: Malate 2017 (AIP)

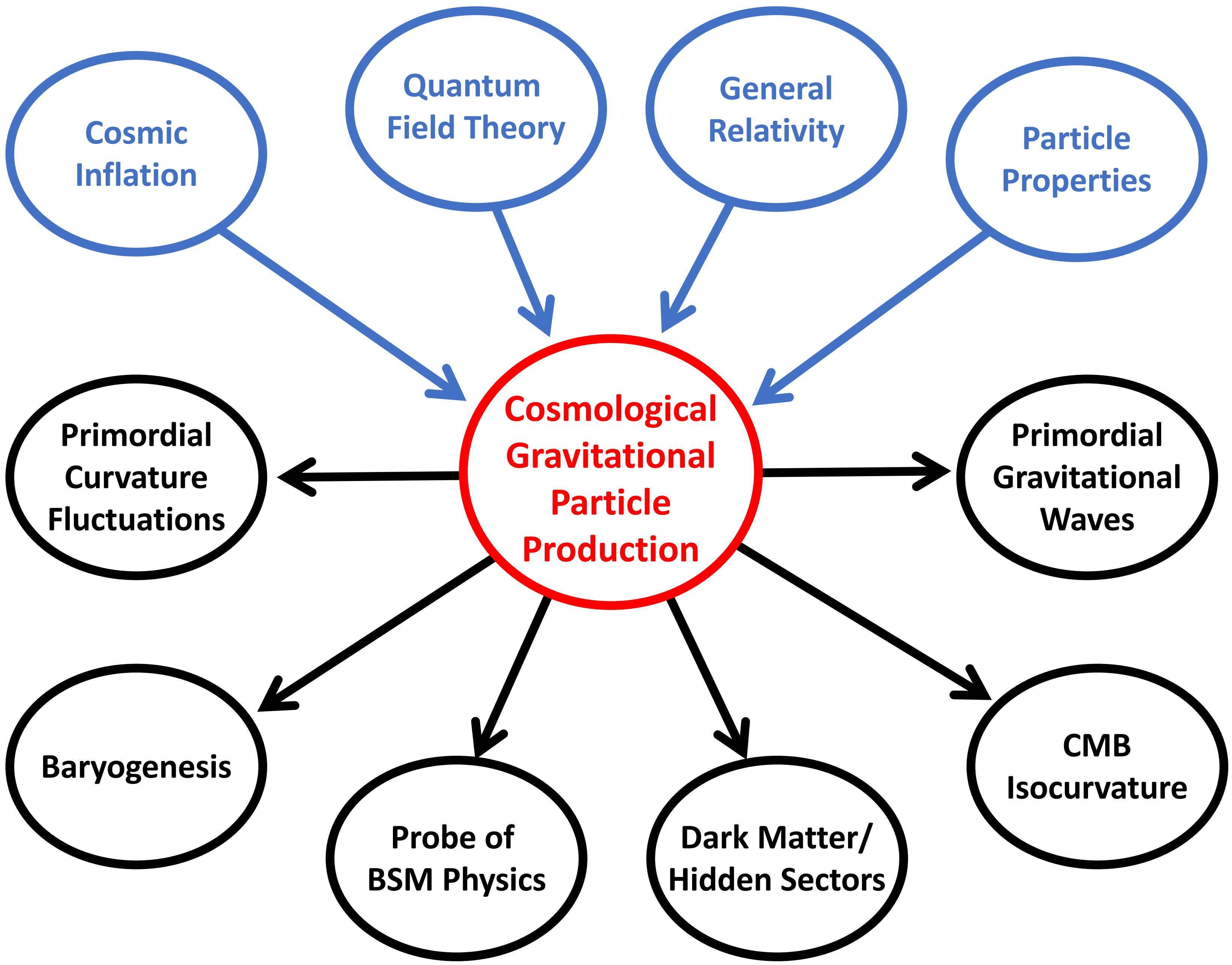
Turn on expansion

$\longleftarrow$ expansion $\longrightarrow$

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

$$\left.\begin{array}{r}\text{Hubble's law}\;\; \mathrm{v} = Hd \\ \mathrm{v} = 1;\;\; d = m^{-1}\end{array}\right\} \Longrightarrow H_{\mathrm{crit}} = m \quad \Longrightarrow \Gamma \propto e^{-m/H}$$

Schrödinger (1939)


Cosmic Inflation
Quantum Field Theory
General Relativity
Particle Properties
Cosmological Gravitational Particle Production
Primordial Curvature Fluctuations
Primordial Gravitational Waves
Baryogenesis
Probe of BSM Physics
Dark Matter/ Hidden Sectors
CMB Isocurvature

Cosmological Gravitational Particle Production (CGPP)

through the Schrödinger mechanism

Chung, EWK, Riotto (1998); Kuzmin & Tkachev (1999)

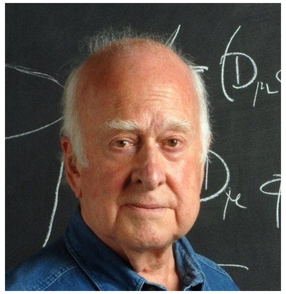
My collaborators:

Ivone Albuquerque	Andrew Long
Edward Basso	Evan McDonough
Christian Capanelli	Guillaume Payeur
Tammi Chowdhury	Toni Riotto
Daniel Chung	Rachel Rosen
Patrick Crotty	Leo Senatore
Michael Fedderke	Alexei Starobinski
Gian Giudice	Keyer Thyme
Lam Hui	Igor Tkachev
Leah Jenks	Jingyuan Wang
Siyang Ling	Mark Wyman

What are Rarita-Schwinger fields?

Standard Model of Particle Physics

Spin 0



Higgs Boson

Spin $1/2$

Leptons & Quarks

Spin 1

Gauge Bosons

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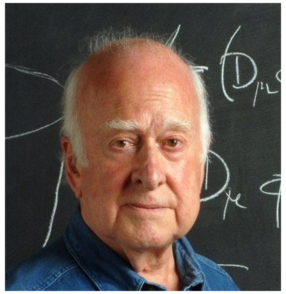

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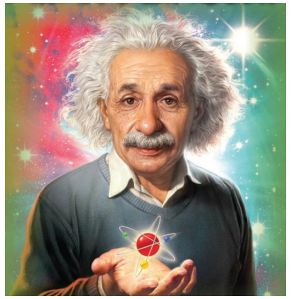
Gravity

Spin 2



Graviton

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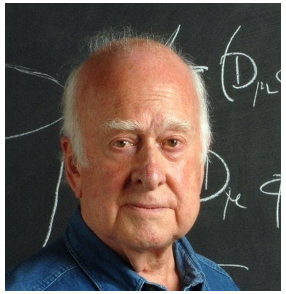

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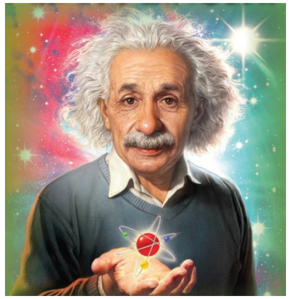
Rarita-Schwinger (R-S)

Spin 2



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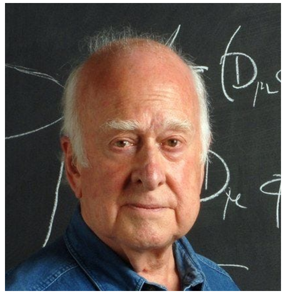

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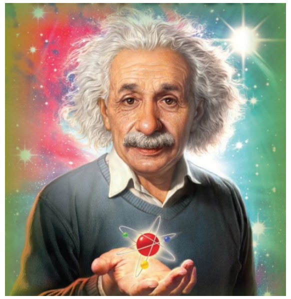

Graviton

R-S fields do not appear in the standard model of particle physics, but are a legitimate subject as a quantum field theory.

What are Rarita-Schwinger fields?

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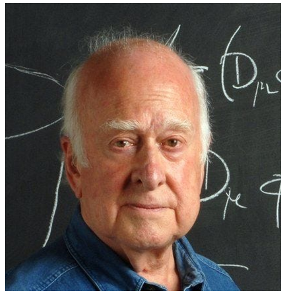

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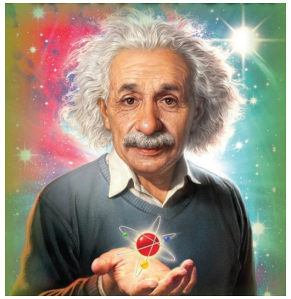

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R-S fields do not appear in the standard model of particle physics, but are a legitimate subject as a quantum field theory.

<u>Massless</u> R-S fields consistent only if coupled to a conserved current as in supersymmetry (Haag–Lopuszanski–Sohnius theorem).

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Standard Model of Particle Physics

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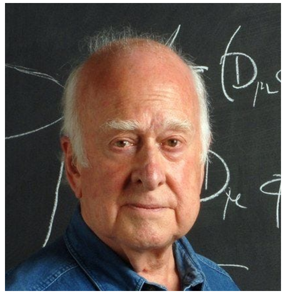

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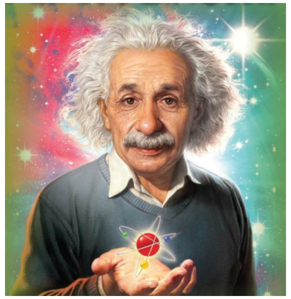

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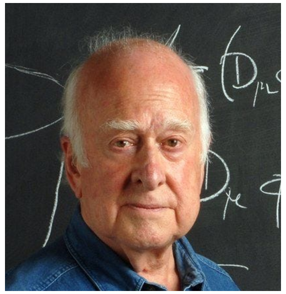

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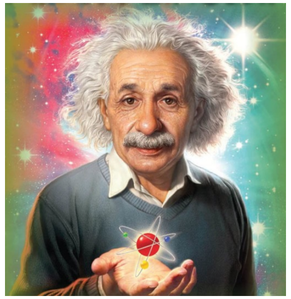

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$$\left(\frac{1}{2},\frac{1}{2}\right)\otimes\left[\left(\frac{1}{2},0\right)\oplus\left(0,\frac{1}{2}\right)\right]=\left(\frac{1}{2},1\right)\oplus\left(0,\frac{1}{2}\right)\oplus\left(1,\frac{1}{2}\right)\oplus\left(\frac{1}{2},0\right).$$

Reducible representation $\underbrace{\left(\frac{1}{2},1\right)\oplus\left(1,\frac{1}{2}\right)}$ $=$ RS field.

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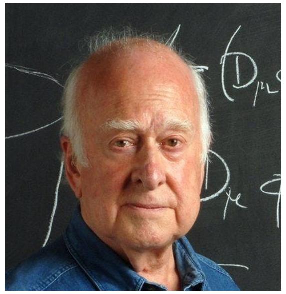

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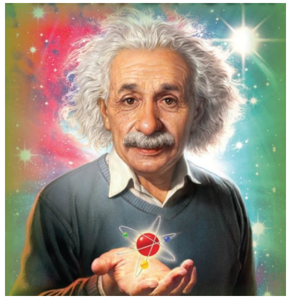

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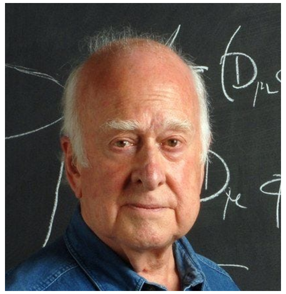
$\left(\frac{1}{2},1\right)\oplus\left(1,\frac{1}{2}\right)$ can be decomposed into irreps. corresponding to $\pm\frac{3}{2}$ and $\pm\frac{1}{2}$ helicity states.

Why study Rarita-Schwinger fields?

Standard Model of Particle Physics

Spin 0



Higgs Boson

Spin $1/2$

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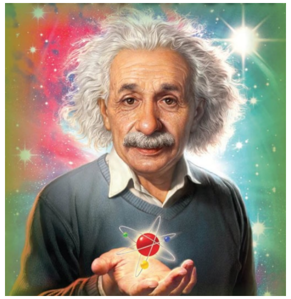
Supergravity

Spin $3/2$

Rarita-Schwinger (R-S)

Spin 2



Graviton

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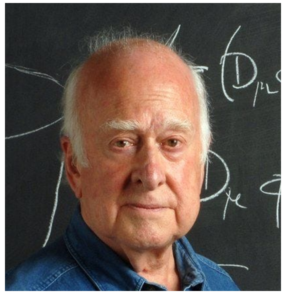

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Rarita-Schwinger (R-S)

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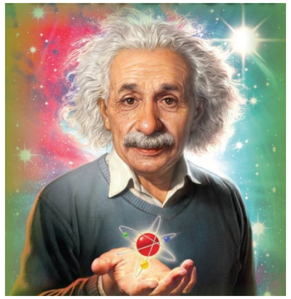


Graviton

In Supergravity (SUGRA), the spin $3/2$ R-S field is the superpartner of the graviton, the *gravitino*.

Gravitino difficult to detect at LHC because of feeble gravitational coupling to SM fields, but …

"Gravitino production leads to important constraints on early universe cosmology." (*Supergravity*, Freedman and Van Proeyen).

"Early universe cosmology (may) lead to important constraints on Supergravity model building." (EWK, Long, McDonough, PRD 2021 & PRL 2021; EWK, Long, McDonough, Wang 2025).

This is a work in progress with Andrew Long, Evan McDonough, and Jingyuan Wang.

Why study CGPP of Rarita-Schwinger fields?

through the Schrödinger mechanism

I've studied CGPP of minimally-coupled scalars, conformally-coupled scalars, Dirac fermions, de Broglie-Proca fields, Kalb-Ramond fields, Fierz-Pauli fields, in one-field inflation models, rapid-turn inflation models, inflation models with non-canonical kinetic terms, Higgs-inflation models, …

Aren't you tired of it?   Don't you have anything better to do?

What could possibly be new with Rarita-Schwinger fields? Two answers:

1. possibility of vanishing sound speed,
2. in SUGRA models, generally RS field (the gravitino) has a dynamical mass.

Our (EWK, Long, McDonough, Wang) project goal is to calculate CGPP of gravitinos.

First step is to understand CGPP of "simple" R-S fields.

This is a progress report.

Rarita-Schwinger field in FRW background

Covariant action for R-S field: $\Psi_\mu =$ vector-spinor

Kallosh, Kofman, Linde, Van Proeyen (1999)
Giudice, Riotto, Tkachev (1999)
EWK, Long, McDonough (2021)

$$S = \int d^4x\, e\left[i\left(\tfrac{1}{4}\bar{\Psi}_\mu \underline{\gamma}^{\mu\nu\rho}\nabla_\nu\Psi_\rho - \tfrac{1}{4}\bar{\Psi}_\mu \overleftarrow{\nabla}_\nu \underline{\gamma}^{\mu\nu\rho}\Psi_\rho\right) - i\,\tfrac{1}{2}m\bar{\Psi}_\mu\gamma^{\mu\nu}\Psi_\nu\right]$$

Specialize to FRW and define new field $\psi_\mu(\eta,\vec{x}) = a^{1/2}(\eta)\Psi_\mu(\eta,\vec{x})$ for canonical kinetic term

Impose constraints from field equations

Fourier decomposition $\psi_\mu(\eta,\vec{x}) = \displaystyle\int \frac{d^3\vec{k}}{(2\pi)^3}\,\psi_{\mu,\vec{k}}(\eta)\,e^{i\vec{k}\cdot\vec{x}}$

Remove non-dynamical DOFs and decompose into helicity states: $\psi_{\mu,\vec{k}} \longrightarrow \psi_{1/2,\vec{k}}$ and $\psi_{3/2,\vec{k}}$

Mode equations become
$$\begin{cases} \left[i\gamma^0\partial_\eta - \vec{k}\cdot\vec{\gamma} - am\right]\psi_{3/2,\vec{k}} = 0 \\ \left[i\gamma^0\partial_\eta - \left(C_A + iC_B\gamma^0\right)\vec{k}\cdot\vec{\gamma} - am\right]\psi_{1/2,\vec{k}} = 0 \end{cases}$$

C_A and C_B are functions of $H,\ R,\ m,\ \dot{m}$

Rarita-Schwinger field in FRW background

Parameterize spinor wavefunctions in terms of helicity eigenspinors with mode functions

$$\chi_{A,3/2,\vec{k}}(\eta),\ \chi_{B,3/2,\vec{k}}(\eta),\ \chi_{A,1/2,\vec{k}}(\eta),\ \chi_{B,1/2,\vec{k}}(\eta)$$

which satisfy

$$\begin{cases} i\partial_\eta \begin{pmatrix} \chi_{A,3/2,k}(\eta) \\ \chi_{B,3/2,k}(\eta) \end{pmatrix} = \begin{pmatrix} am & k \\ k & -am \end{pmatrix} \begin{pmatrix} \chi_{A,3/2,k}(\eta) \\ \chi_{B,3/2,k}(\eta) \end{pmatrix} \\ \\ i\partial_\eta \begin{pmatrix} \chi_{A,1/2,k}(\eta) \\ \chi_{B,1/2,k}(\eta) \end{pmatrix} = \begin{pmatrix} am & c_s\, k \\ c_s^*\, k & -am \end{pmatrix} \begin{pmatrix} \chi_{A,1/2,k}(\eta) \\ \chi_{B,1/2k}(\eta) \end{pmatrix} \end{cases}$$

c_s is complex sound speed
$c_s = C_A + i\, C_B$

Helicity-$3/2$ mode equation is just like Dirac field

Helicity-$1/2$ mode equation is more "interesting"

Eigenvalues of $1/2$ mode equation are $\pm\sqrt{|c_s|^2k^2 + a^2m^2}$

Vanishes for R-S fields, but can be nonzero for gravitinos

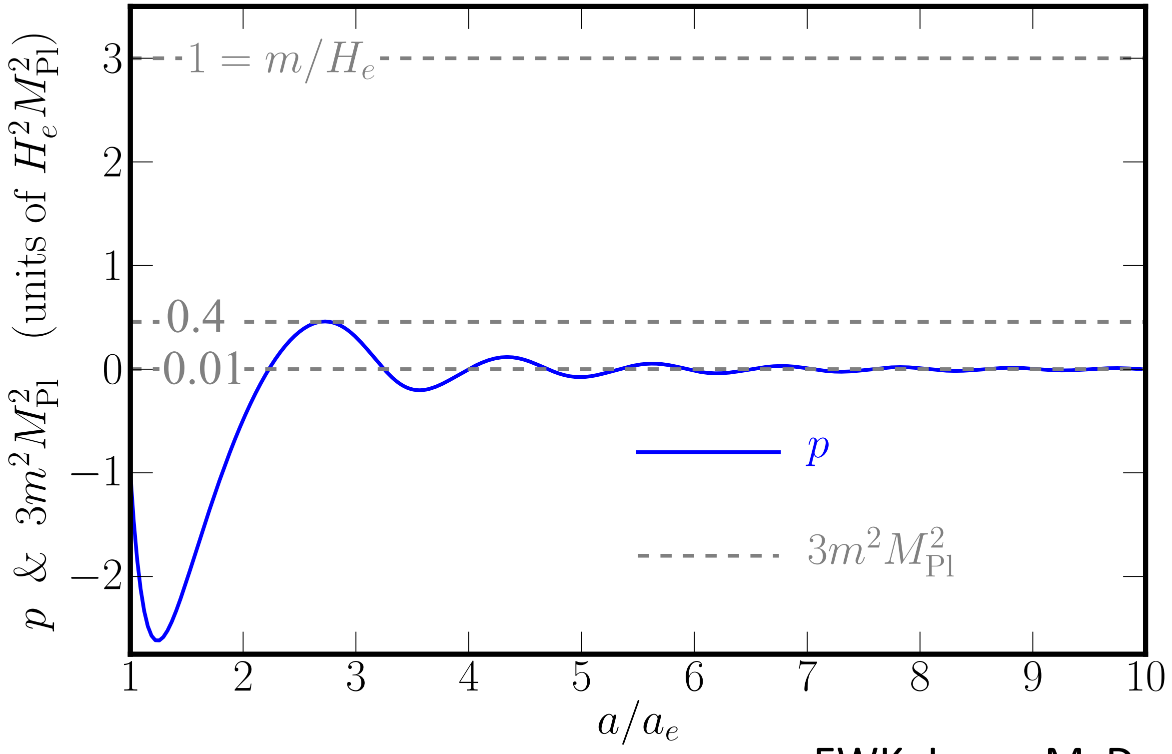
$$|c_s|^2 = \frac{1}{9(H^2+m^2)^2}\left[\left(3m^2 - \tfrac{1}{3}R - H^2\right)^2 + 4\dot{m}^2\right]$$

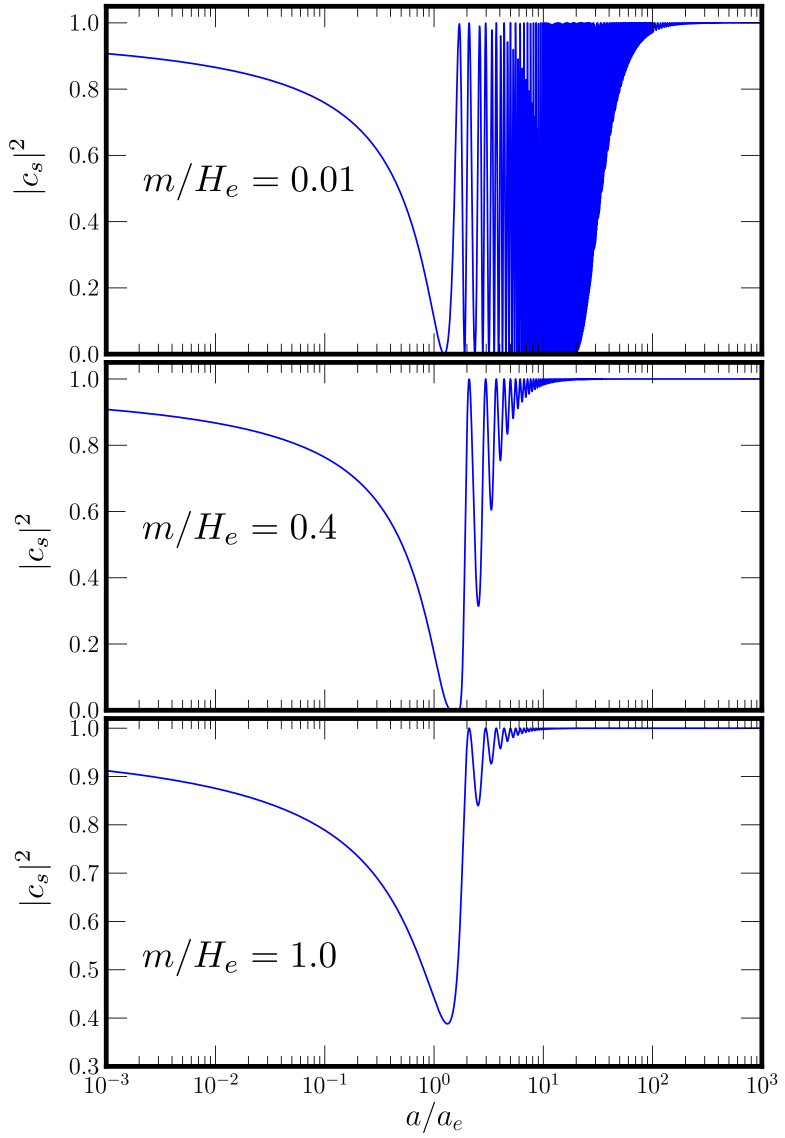
Sound speed can vanish

New feature (or is it a bug?): sound speed can vanish!

$$|c_s| = \frac{\left|3m^2 - \frac{1}{3}R - H^2\right|}{3m^2 + 3H^2} = \frac{\left|3m^2 - p/M_{\rm Pl}^2\right|}{3m^2 + \rho/M_{\rm Pl}^2}$$

$|c_s| = 1$ in dS ($p = -\rho$) $\quad |c_s| = 0$ when $p = 3m^2 M_{\rm Pl}^2$





EWK, Long, McDonough (2021)

$m/H_e \gtrsim 0.4 \leftrightarrow |c_s| = 0$ avoided

$m/H_e \lesssim 0.4 \leftrightarrow |c_s| = 0$ occurs

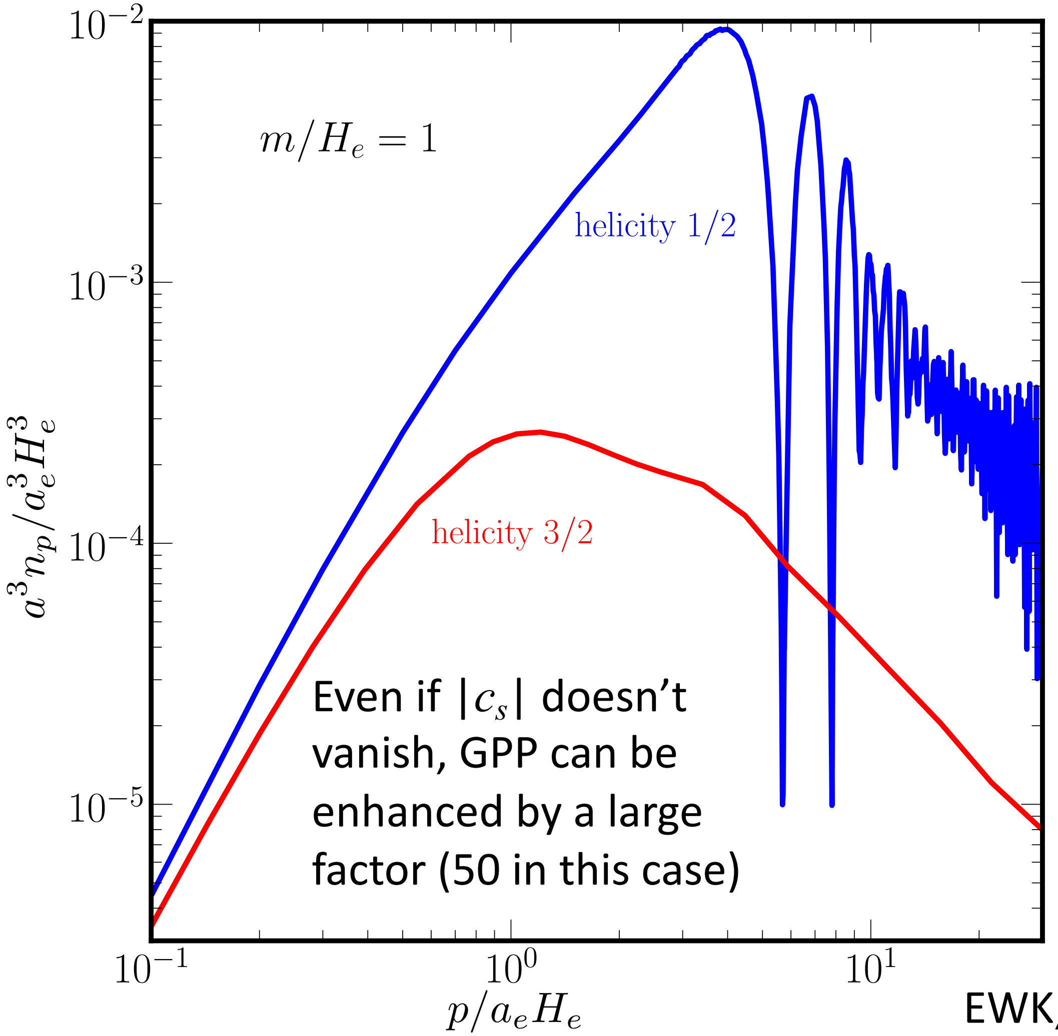
Vanishing sound speed enhances GCPP

c_s varies for helicity-1/2 mode

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

If $|c_s| > 0$, ω_k^2 proportional to k^2, and CGPP suppressed for high-k modes

If $|c_s| = 0$, ω_k^2 independent of k^2, and CGPP <u>unsuppressed</u> for high-k modes

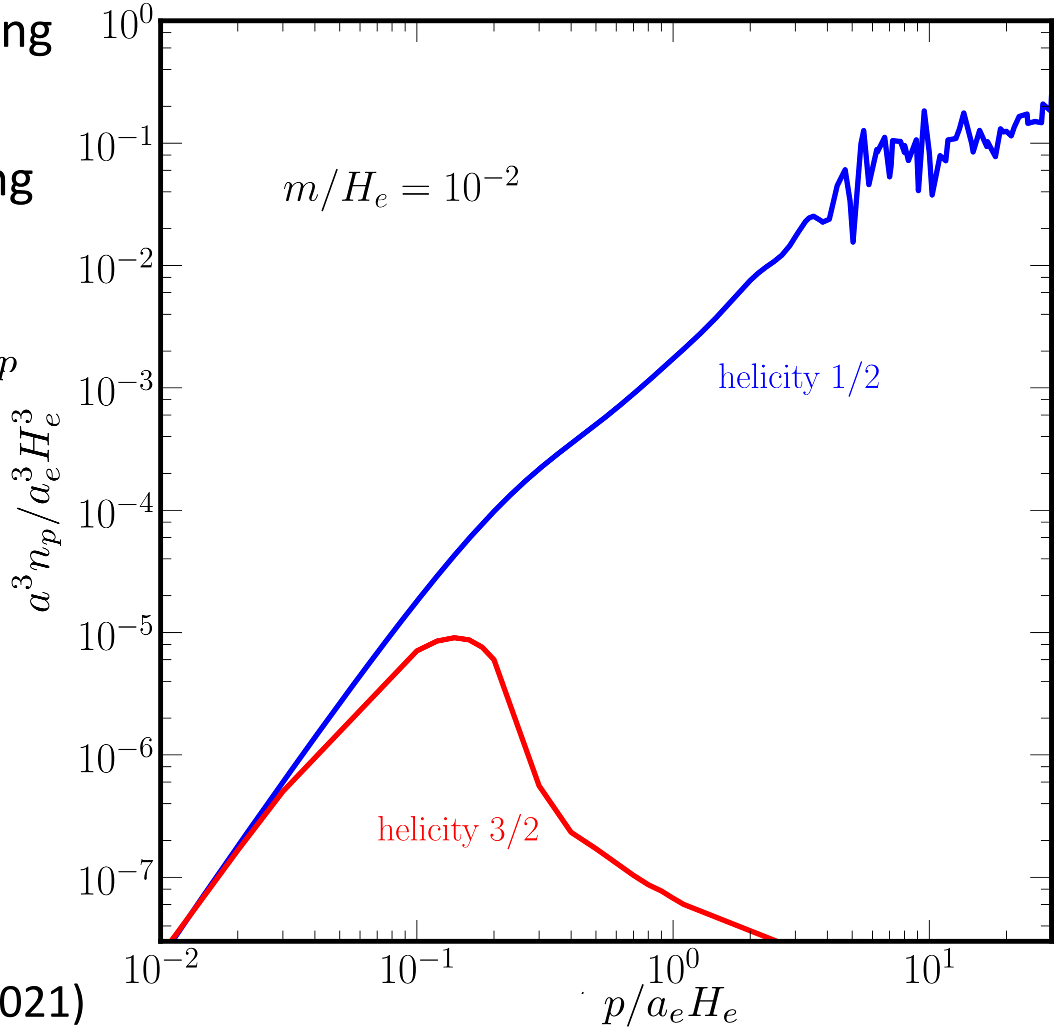


$a^3 n_p$ is the comoving spectral density

$a^3 n$ is the comoving number density

$$a^3 n = \int \frac{dp}{p} a^3 n_p$$

If $a^3 n_p$ peaked,
$a^3 n \approx$ peak of $a^3 n_p$



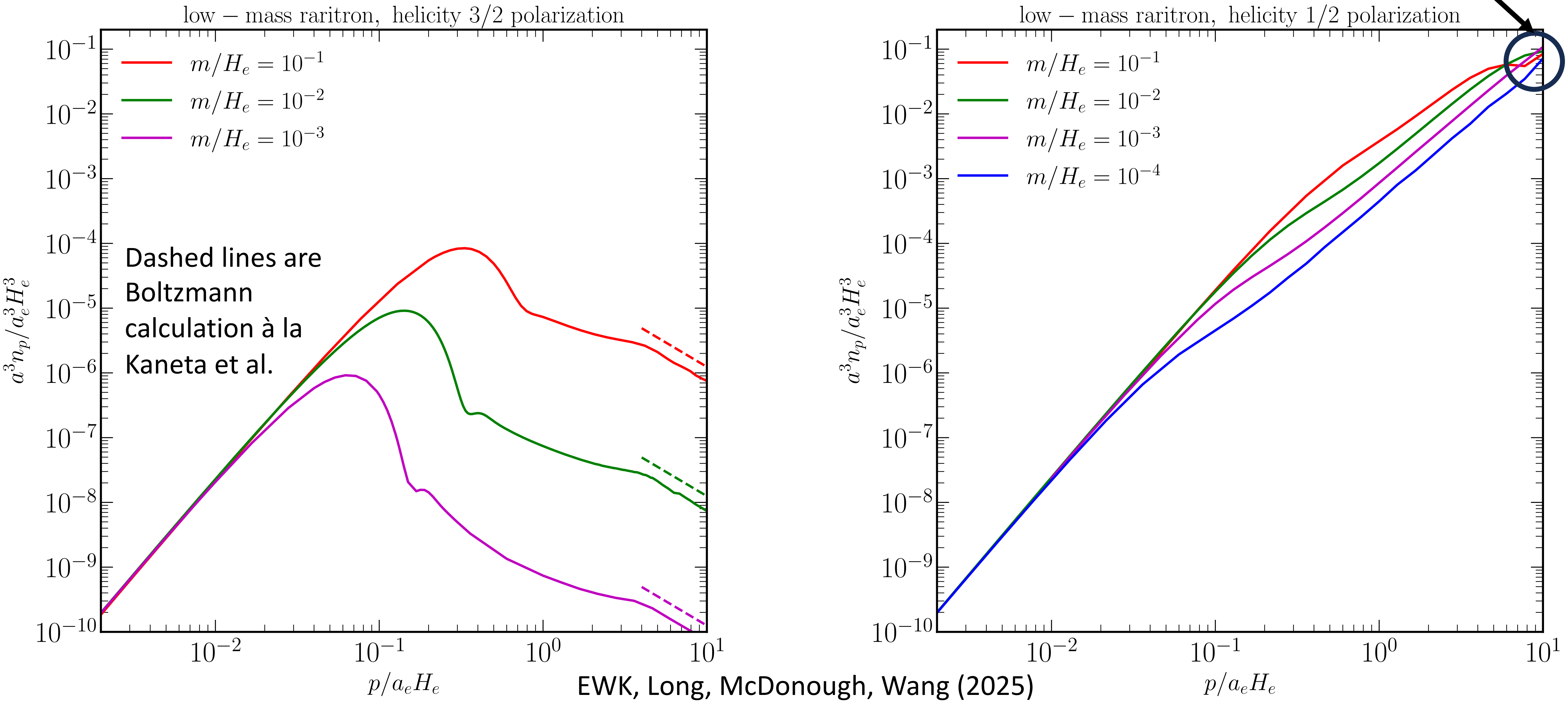
EWK, Long, McDonough (2021)

Vanishing sound speed enhances GCPP

Call it a "raritron" (Kaneta, Ke, Mambrini, Olive, Verner 2023)

Unresolved high-p behavior p^0, p^1, p^2, p^3 ?

Low mass raritron: catastrophic production for ½ helicity

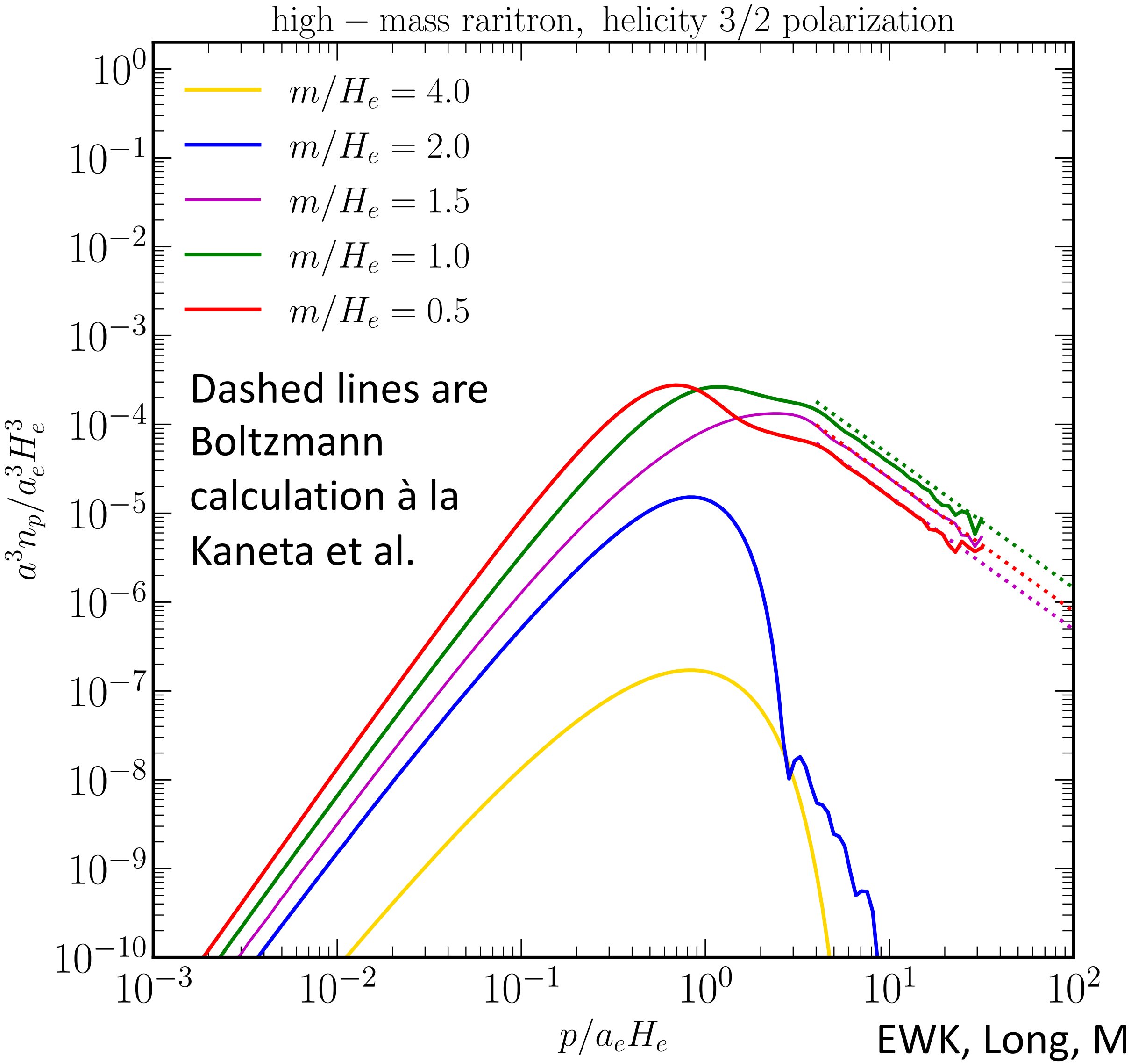


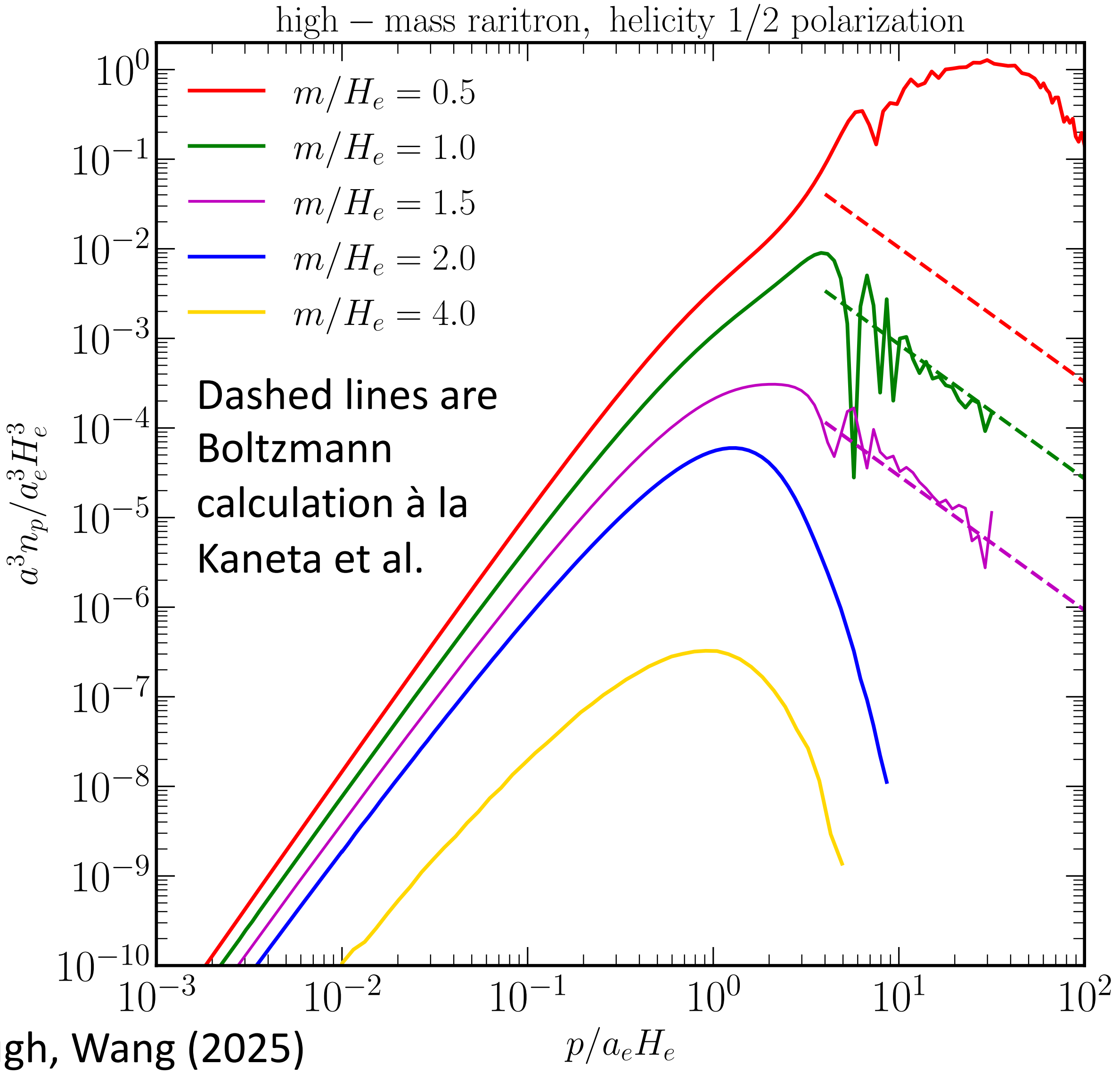
EWK, Long, McDonough, Wang (2025)

Vanishing sound speed enhances GCPP

Call it a "raritron" (Kaneta, Ke, Mambrini, Olive, Verner 2023)

High mass raritron: no catastrophic production for ½ helicity, but n_k larger





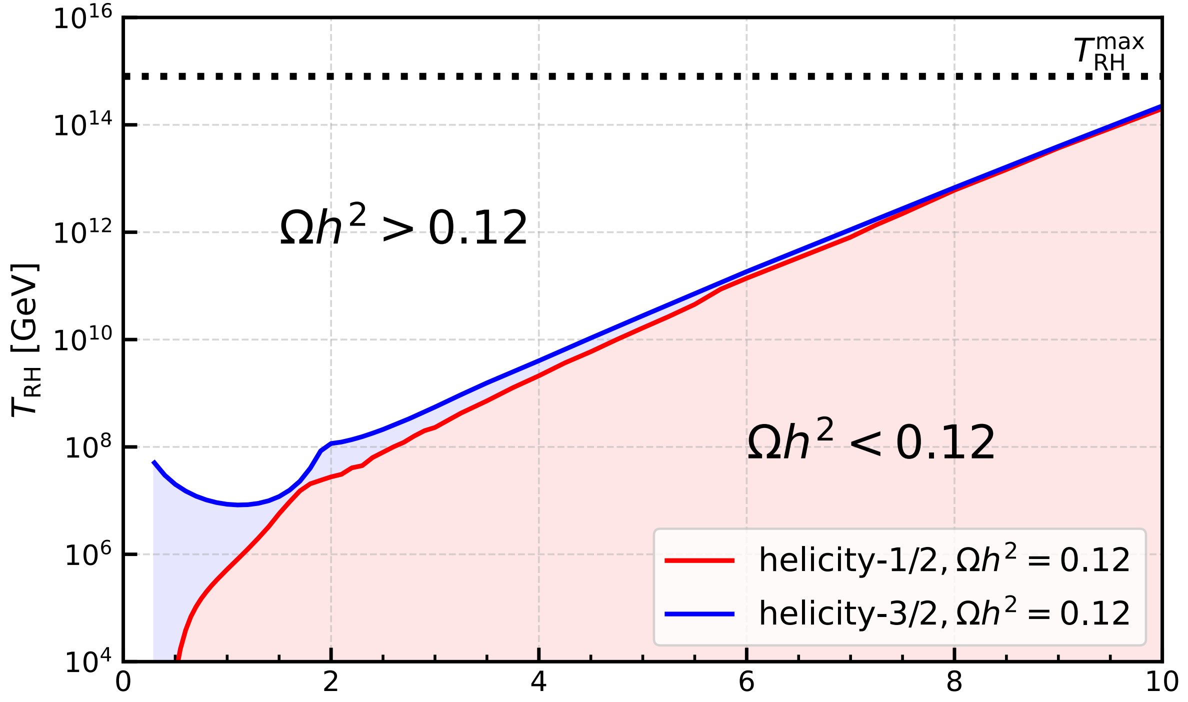
EWK, Long, McDonough, Wang (2025)

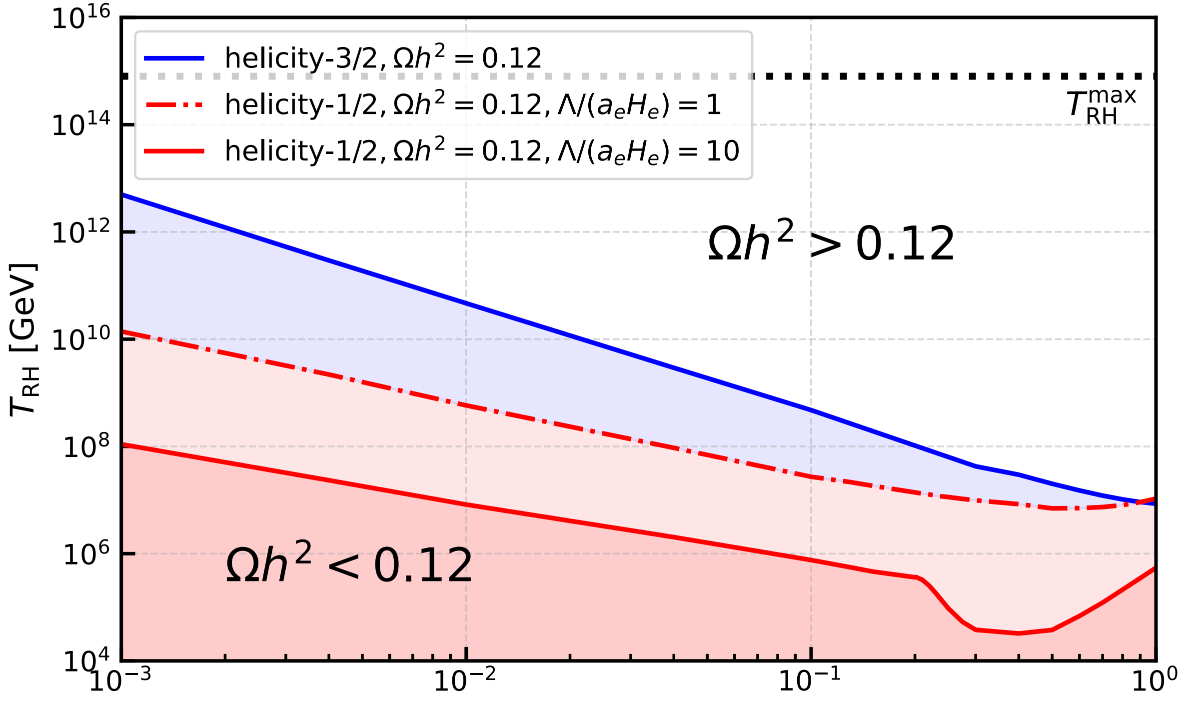
Rarita-Schwinger field can be dark matter

$$\boxed{\frac{\Omega h^2}{0.12} \approx \left(\frac{m}{H_e}\right)\left(\frac{H_e}{10^{12}\ \mathrm{GeV}}\right)^2\left(\frac{T_{\mathrm{RH}}}{10^{9}\ \mathrm{GeV}}\right)\left(\frac{1}{10^{-5}}\cdot\frac{a^3 n}{a_e^3 H_e^3}\right)}$$

- For high-mass raritrons ($m/H_e \gtrsim 0.4$):
  - Helicity ½ dominates, esp. for $m \lesssim 1.5\ H_e$.
  - n_k decreases at large k, n and Ω finite.
  - Could be dark matter for $m \lesssim 10\ H_e$.

- For low-mass raritrons ($m/H_e \lesssim 0.4$):
  - Helicity ½ dominates.
  - n_k unbounded at large k, so must either introduce cutoff, or have $\dot{m} \neq 0$ (SUGRA?)
  - Could be dark matter

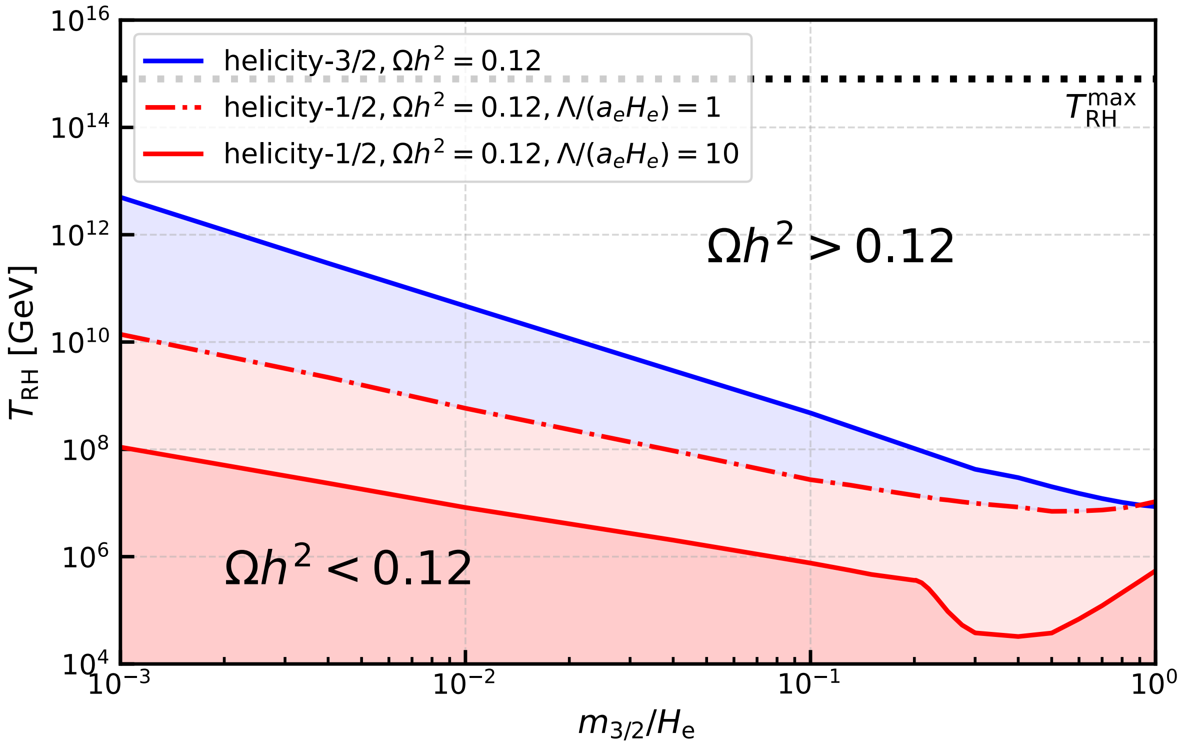




EWK, Long, McDonough, Wang (2025)

Rarita-Schwinger field can be dark matter

- For low-mass raritrons ($m_{3/2}/H_e \lesssim 0.1$):
  - For helicity $1/2$, $T_{\rm RH}$ scales as $(m_{3/2}/H_e)^{-1}$ to obtain $\Omega h^2 = 0.12$
  - For $\Lambda/a_e H_e = 10$, if $T_{\rm RH} = 10^{15}\,\mathrm{GeV}$, $\Omega h^2 = 0.12$ for $m_{3/2}/H_e = 10^{-10}$
  - Can have very light raritron be dark matter
  - If cutoff $\Lambda > 10\ a_e H_e$, even lighter raritron possible for $\Omega h^2 = 0.12$
  - Similar conclusion in Kaneta et al., but different calculation



EWK, Long, McDonough, Wang (2025)

Varying R-S mass?

Varying rarirton mass to remove catastrophic helicity ½ production

- Sound speed is complex, $c_s = C_A + i\, C_B$
- Now just focus on $|c_s|^2$ and consider $|c_s|^2 = 1$

$$|c_s|^2 = \frac{1}{9(H^2+m^2)^2}\left[\left(3m^2 - \tfrac{1}{3}R - H^2\right)^2 + 4\dot{m}^2\right]$$

$$|c_s(N)|^2 = 1 \Rightarrow \left(\frac{dm}{dN}\right)^2 = H^2\left[1 + \frac{R}{12H^2}\right]\left[2 - \frac{R}{3H^2} + 6\frac{m^2}{H^2}\right]$$

$R =$ Ricci scalar
$N = \ln(a/a_e)$

$$\frac{dm}{dN} = \pm H\left[\frac{\dot{\phi}^2}{2M_{\rm Pl}^2 H^2}\right]^{1/2}\left[\frac{V(\phi)}{M_{\rm Pl}^2 H^2} + 3\frac{m^2}{H^2}\right]^{1/2}$$

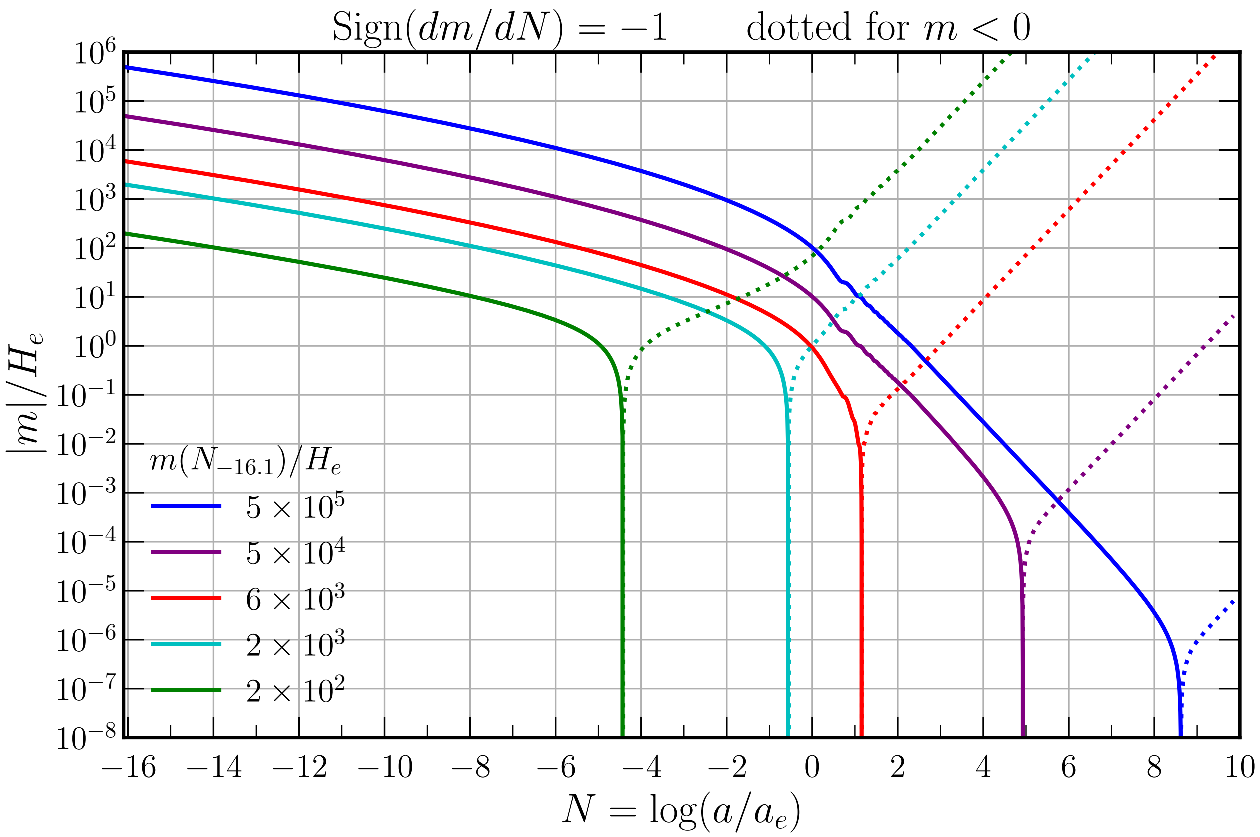
Ambiguity in choice of sign.

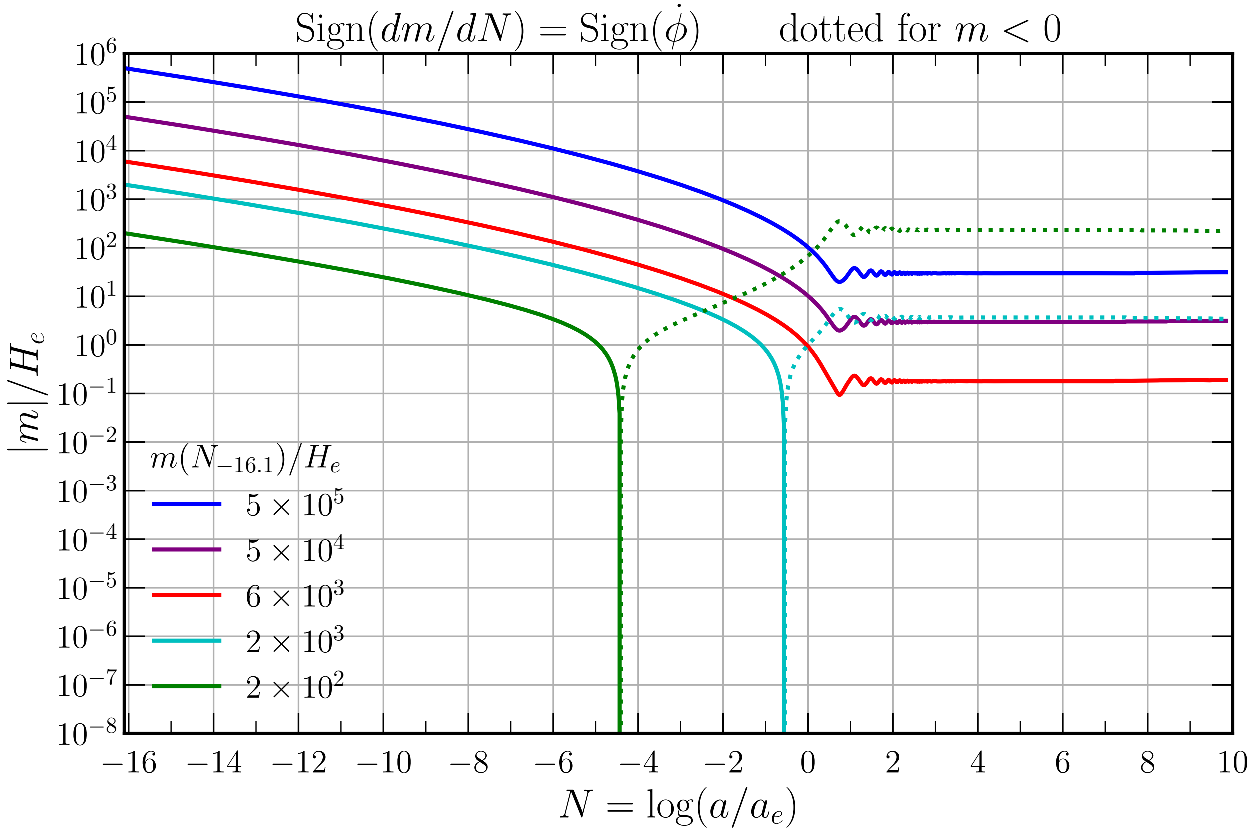
When $dm/dN = 0$, can change sign.

$dm/dN = 0$ when $\dot{\phi} = 0$ or when $m = 0$ and $V(\phi) = 0$.

Varying R-S mass?

$|c_s| = 1$ to remove catastrophic helicity ½ production? Require $\dot{m} \neq 0$. BUT WHY?





What fixes initial value of m?

$m \to \infty$ at late time. Not acceptable.

Note: for fermion sign of m doesn't matter.

What fixes initial value of m?

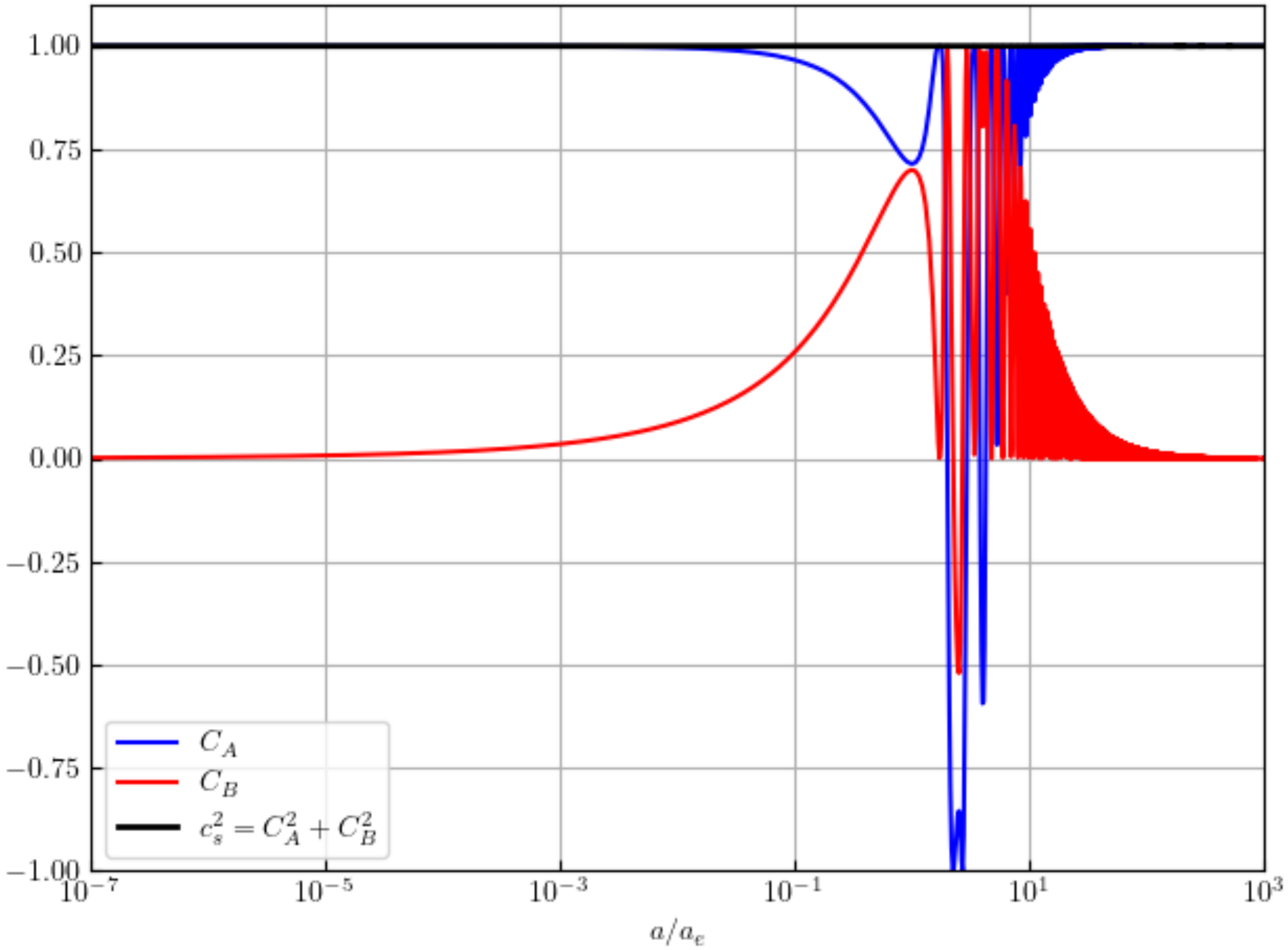
Sign of dm/dN changes every time $\dot{\phi}$ goes through 0.

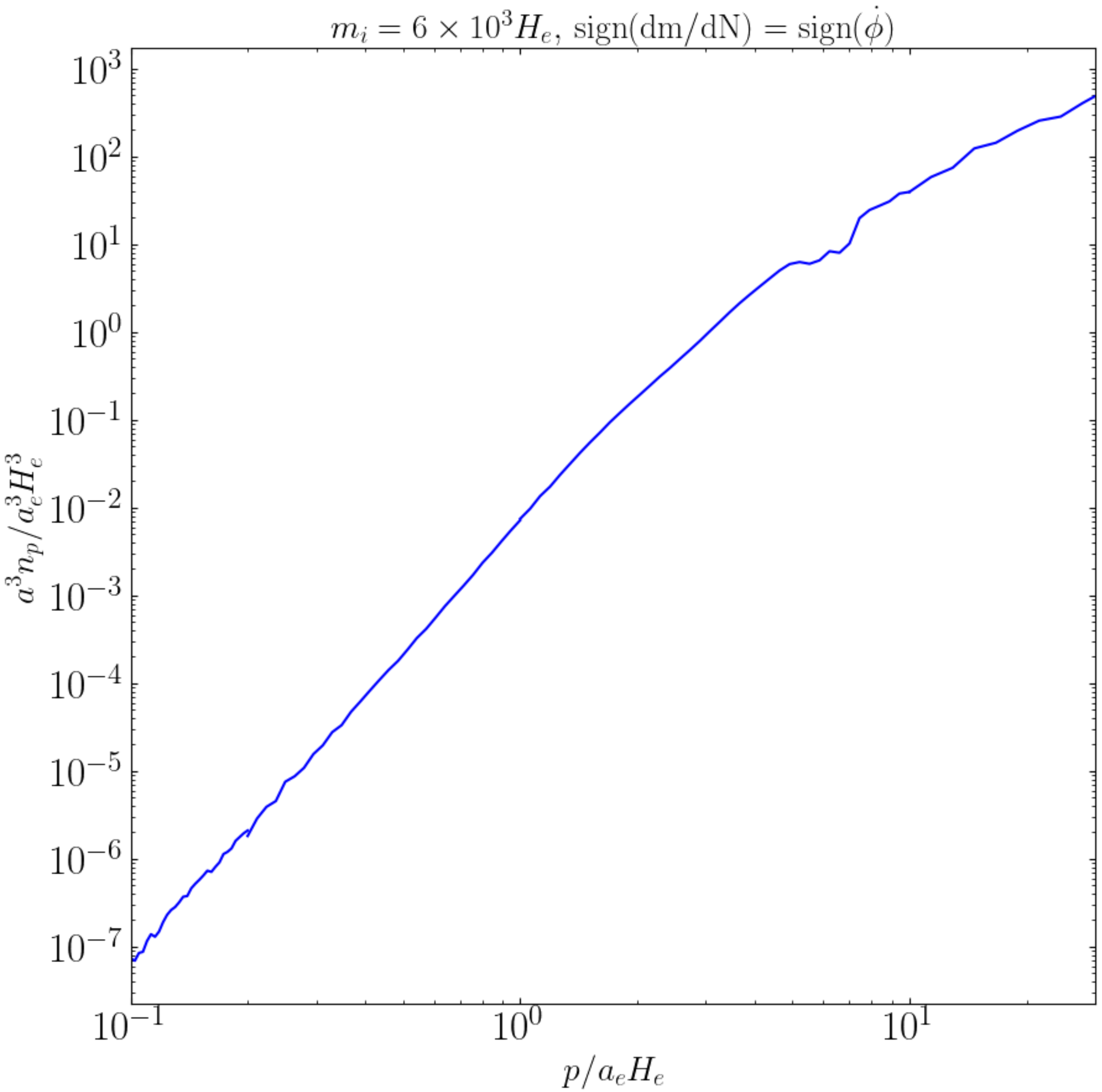
Nice m behavior at late time, but WHY change sign?

Answers must lie with Supergravity

Varying R-S mass?

- Even with $|c_s|^2 = 1$, can still have catastrophic production.
- Sound speed is complex: $c_s = C_A + i\, C_B$.
- It can be pure imaginary when $C_A = 0$!





Gravitino in FRW background

Spin-$3/2$ particles arise in theories of supergravity; $s = 3/2$ gravitino is superpartner of $s = 2$ graviton

Does supergravity have a catastropic production of gravitinos? It depends on the model!

For models with a single chiral superfield Φ with Kahler potential $K(\Phi, \bar{\Phi}) = \Phi\bar{\Phi}$, superpotential $W(\Phi) = \dfrac{1}{2} m_\phi \Phi^2$

$$m_{3/2} = e^{K(\Phi,\bar{\Phi})/2M_{\rm Pl}^2} \frac{W(\Phi)}{M_{\rm Pl}^2} = e^{\phi^2/4M_{\rm Pl}^2} \frac{m_\phi}{4M_{\rm Pl}^2} \phi^2$$

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2 \; e^{\phi^2/2M_{\rm Pl}^2} \left(1 + \frac{\phi^2}{8M_{\rm Pl}^2} + \frac{\phi^4}{16M_{\rm Pl}^2}\right)$$

$$\dot{m}_{3/2} = \mathrm{Sign}(\phi\dot{\phi}) \left[\frac{\dot{\phi}^2}{2M_{\rm Pl}^2}\right]^{1/2} \left[\frac{V(\phi)}{M_{\rm Pl}^2} + 3m_{3/2}^2\right]^{1/2}$$

Time-dependent gravitino mass (depends on rolling inflaton) $\Rightarrow |c_s| = 1$ at all times & no catastrophic production.

But issues:

1. SUSY restored at late times when $\phi = 0$
2. model doesn't inflate

EWK, Long, McDonough (2021) × 2
EWK, Long, McDonough, Wang (2025)

Gravitino in FRW background

For models with two chiral superfields

$|c_s|$ depends on relative orientation of inflaton direction & SUSY breaking direction

$|c_s| = 0$ occurs in models with a nilpotent superfield $S^2 = 0$ and orthogonal constraint $S \cdot (\Phi - \bar{\Phi}) = 0$

EWK, Long, McDonough (2021) × 2

But even more complications:

why not three chiral superfields

gravitino may mix with inflation

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

many other fields

vanishing sound speed may not be catastrophic

Dudas, Garcia, Mambrini, Olive, Peloso, Verner (2021)

Antoniadis, Benaki, Ke (2021)

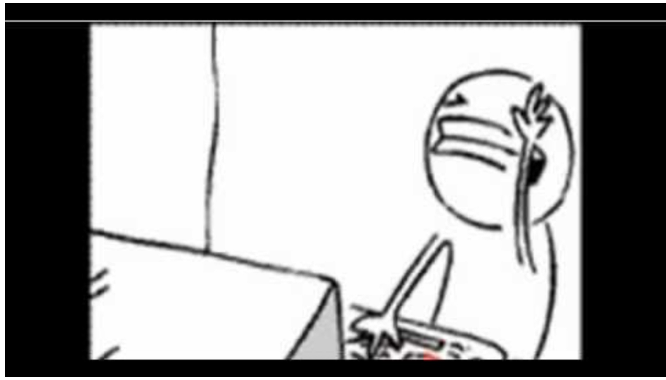
Rarita-Schwinger Fields and Cosmology

- Preliminary results!

- It's still a work in progress (things take longer than they do).

- What we (EWK, Long, McDonough, Wang) plan to accomplish in the first paper:
  - Convincingly demonstrate (again) that Boltzmann approach is not the compete picture.
  - Calculate relic density for R-S fields, including possibility of zero sound speed. (Kaneta, Ke, Mambrini, Olive, Verner (2023) ignored zero sound speed and only considered Boltzmann)
    - If constant mass RS, must employ cutoff for low masses.
  - Explore parameter space for R-S field (raritron) to be dark matter.
  - Explore possibilities for an R-S field for varying m.

- In a subsequent paper we will consider CGPP of gravitino, inflatino, goldstino, (s)goldstino, whateverino in several Supergravity models.



My experience with Supergravity
https://youtu.be/ozA0VmIsCNs?feature=shared

Rarita-Schwinger Fields and Cosmology

Sep 22 – 25, 2025

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