Cosmological Gravitational Particle Production of Massive Spin-2 Particles [2302.04390; JHEP 05 (2023) 181]

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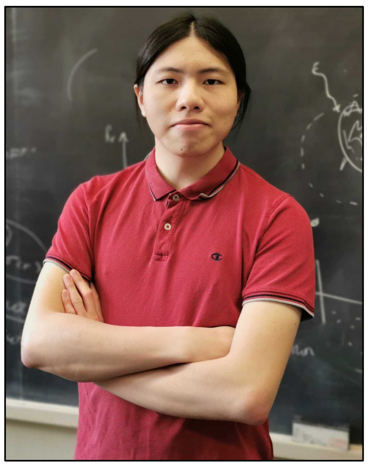

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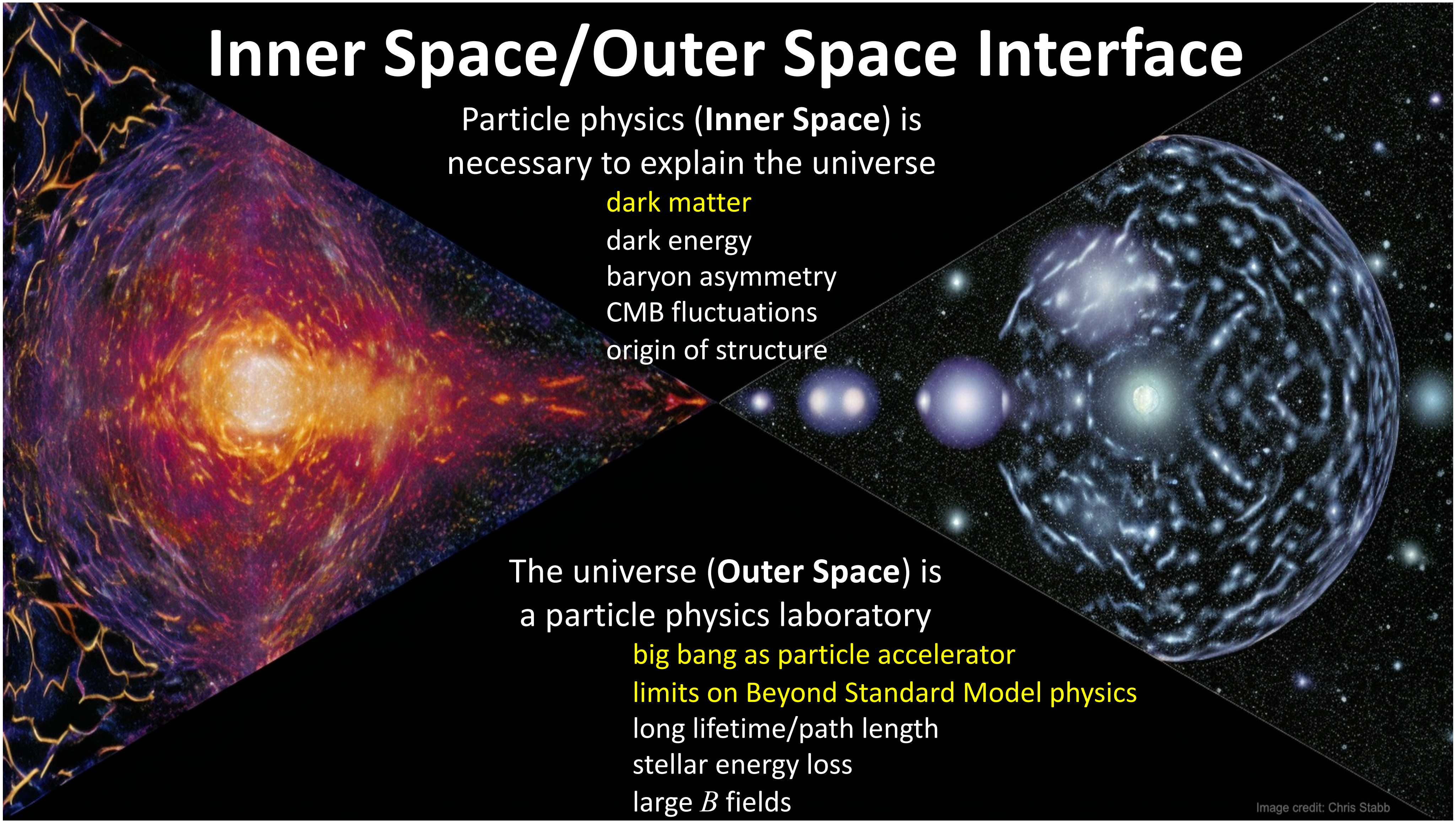

Inner Space/Outer Space Interface
Particle physics (Inner Space) is
necessary to explain the universe
dark matter
dark energy
baryon asymmetry
CMB fluctuations
origin of structure
The universe (Outer Space) is
a particle physics laboratory
big bang as particle accelerator
limits on Beyond Standard Model physics
long lifetime/path length
stellar energy loss
large B fields
Image credit: Chris Stabb

Inner Space/Outer Space Interface

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

Requires: $\begin{cases} \text{1. at some point } T > m \\ \text{2. particle has SM interactions} \end{cases}$

BUT

Maximum temperature of the radiation-dominated universe is the "reheat" temperature after inflation, $T_{\rm RH}$

$T_{\rm RH}$ may be as low as $8\ \mathrm{MeV}$ (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)

Image credit: Chris Stabb


The big question: origin of dark matter?
JWST image

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. CDM.
- "Detectable" by direct detection, indirect detection, decay products, production at colliders
- Just BSM, e.g., low-energy SUSY!

But WIMPs have stubbornly evaded detection!

What if DM interacts only <u>gravitationally</u> with SM?

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

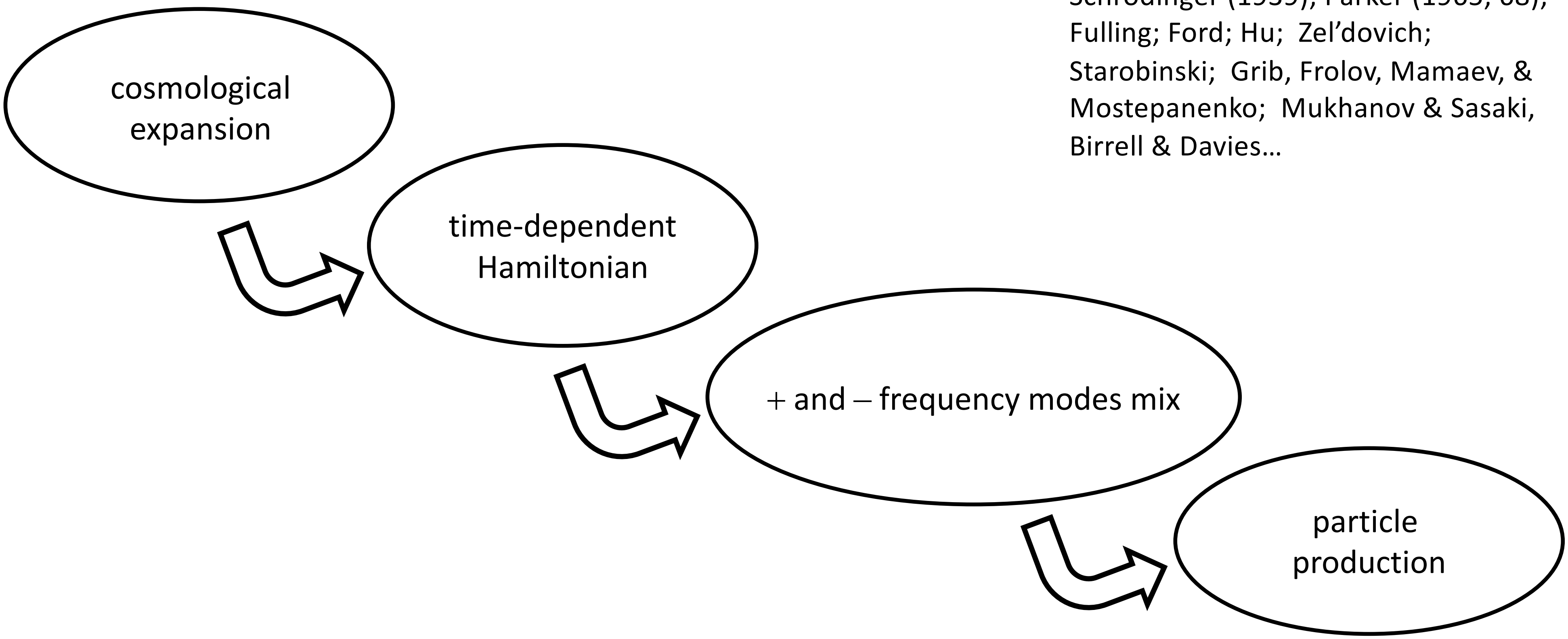
Cosmological Gravitational Particle Production (CGPP) can be the origin of DM!

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

CGPP Through Expansion of the Universe

- 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…



Representation	Particle	1-point function Dark Matter	2-point function CMB Isocurvature	3-point function CMB Nongaussian
(0,0)	Conformally Coupled Scalar $\xi = 1/6$ (use as template)	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) ⊕ (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) ⊕ (0,1)	2-Form (Pseudo) Vector (e.g., Kalb-Ramond)	Capanelli, Jenks, EWK, & McDonough (next week)		
(1/2,1) ⊕ (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)		

Metric Perturbations About Minkowski Spacetime

Start with EH action: $S[g_{\mu\nu}] = \int d^4x \sqrt{-g}\, \frac{M_P^2}{2} R[g]$

Linearize about Minkowski spacetime: $g_{\mu\nu} \to \eta_{\mu\nu} + \frac{2}{M_P} h_{\mu\nu} \qquad h = \eta^{\mu\nu} h_{\mu\nu}$

$$S[h_{\mu\nu}] = \int d^4x \left[-\tfrac{1}{2} \nabla_\lambda h_{\mu\nu} \nabla^\lambda h^{\mu\nu} + \nabla_\mu h^{\nu\lambda} \nabla_\nu h^\mu{}_\lambda - \nabla_\mu h^{\mu\nu} \nabla_\nu h + \tfrac{1}{2} \nabla_\mu h \nabla^\mu h \right]$$

We will be careful about counting degrees of freedom:

$h_{\mu\nu}$:	16	– 6	– 4	– 4	=	2
		symmetric	gauge	transverse/traceless		helicity modes of massless graviton ±2, or $\times$, $+$

Now Add Fierz-Pauli (1939) Mass Term(s)

(see reviews by Hinterbichler 1105.3735; de Rahm 1401.4173)

$$\delta S[h_{\mu\nu}] = \int d^4x \left[-\tfrac{1}{2}m_1^2 h_{\mu\nu}h^{\mu\nu} - \tfrac{1}{2}m_2^2 h^2\right]$$

Introduces unwanted 6th degree of freedom (a ghost) of mass $m^2_{\text{ghost}} = \dfrac{m_1^2}{4}\dfrac{m_1^2 + 4m_2^2}{m_1^2 + m_2^2}$

So, choose $m_2^2 = -m_1^2$ to banish ghost to ∞ (but no symmetry enforces this!)

$$\delta S[h_{\mu\nu}] = \int d^4x \left[-\tfrac{1}{2}m^2 \left(h_{\mu\nu}h^{\mu\nu} - h^2\right)\right]$$

Fierz-Pauli mass term

Spin-2 theories will be haunted by the spectre of ghosts

Degrees of freedom as expected

$h_{\mu\nu}$:	16	$-\,6$	$-\,1$	$-\,4$	$=\ 5$
		symmetric	gauge	transverse/traceless	polarization modes ± 2, ± 1, 0

Boulware—Deser Ghost

Boulware and Deser (1972) pointed out that Fierz-Pauli tuning breaks down with generic nonlinear extensions of Fierz-Pauli, and a sixth ghostly degree of freedom arises (zombie ghost?).

Once thought that all Lorentz-invariant massive gravity theories were ghostly, until …

… de Rahm-Gabadadze-Tolley (dRGT) developed a ghost-free massive gravity theory in 2010.

dRGT introduced second "reference" metric, taken to be Minkowski. Metrics interact via potential $V(\mathbb{X};\beta_n)$.

Extended/completed to general metric by Hassan & Rosen → ghost-free bigravity (2011).

This is our starting point. Field content: two metric fields, $g_{\mu\nu}$ and $f_{\mu\nu}$, coupled to two scalar fields, ϕ_g and ϕ_f.

It's not massive gravity. Massless graviton + additional massive spin-2 field.

Bigravity With Minimal Coupling To Matter (Minimal Model)

$$S = \int \mathrm{d}^4x \left[\frac{M_g^2}{2}\sqrt{-g}\, R[g] + \frac{M_f^2}{2}\sqrt{-f}\, R[f] - m^2 M_*^2 \sqrt{-g}\, V(\mathbb{X};\beta_n) + \sqrt{-g}\,\mathcal{L}_g(g,\phi_g) + \sqrt{-f}\,\mathcal{L}_f(f,\phi_f) \right]$$

Kinetic terms for f and g + dRGT potential + Matter Lagrangians

dRGT Potential: $\mathbb{X}^\mu{}_\nu = (\sqrt{g^{-1}f})^\mu{}_\nu$

$$V(\mathbb{X};\beta_n) \equiv \sum_{n=0}^{4} \beta_n S_n(\mathbb{X})\,, \qquad S_n(\mathbb{X}) \equiv \mathbb{X}^{\mu_1}_{[\mu_1} \ldots \mathbb{X}^{\mu_n}_{\mu_n]}$$

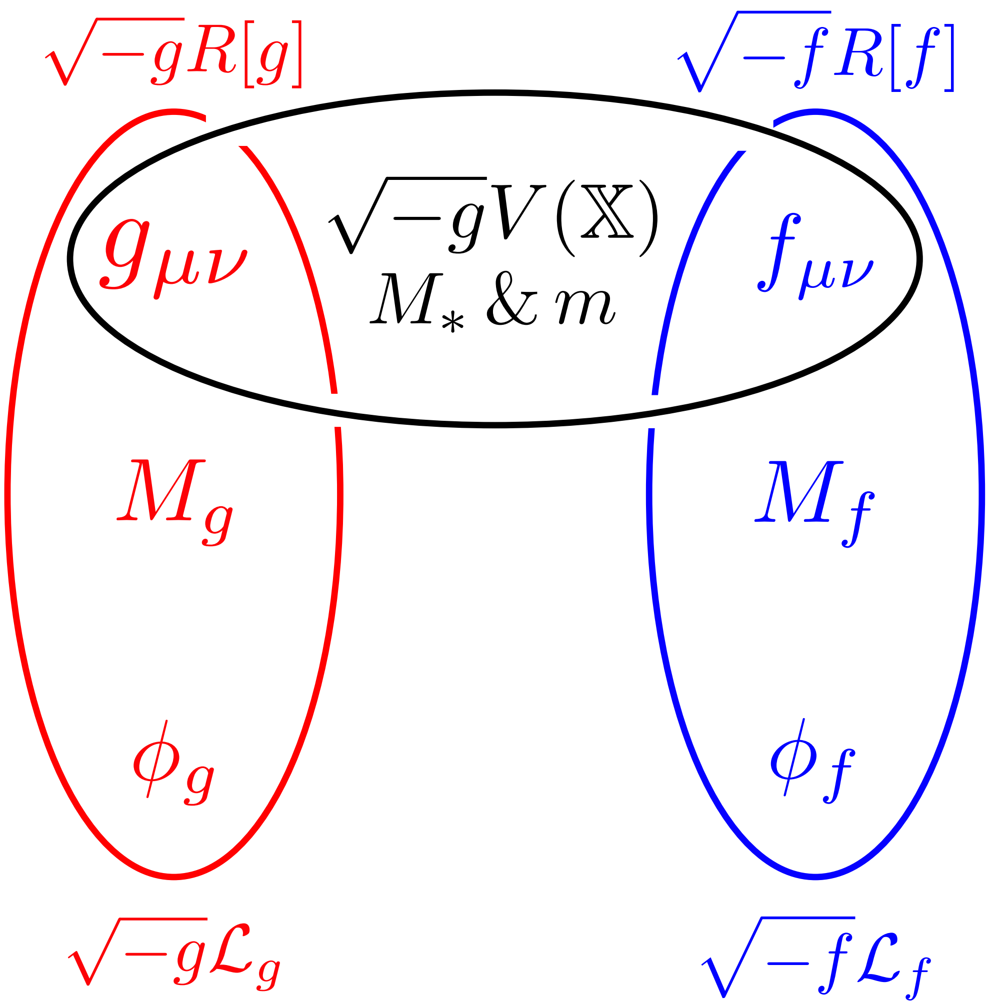
Matter Lagrangians:

$$\left.\begin{aligned} \mathcal{L}_g(g,\phi_g) &= -\tfrac{1}{2} g^{\mu\nu}\nabla_\mu\phi_g\nabla_\nu\phi_g - V_g(\phi_g) \\ \mathcal{L}_f(f,\phi_f) &= -\tfrac{1}{2} f^{\mu\nu}\nabla_\mu\phi_f\nabla_\nu\phi_f - V_f(\phi_f) \end{aligned}\right\} \text{Source FRW background}$$

After sausage making, want to end with: massless spin–2, massive spin–2, two scalar fields

DOFs: $2 + 5 + 2 = 9$

Inflationary Bigravity



Perturbations, Backgrounds, Mirroring (Bar Denotes Background)

Tensor sector

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \frac{2}{M_g} h_{\mu\nu}$$

$$f_{\mu\nu} = \bar{f}_{\mu\nu} + \frac{2}{M_f} k_{\mu\nu}$$

$$\bar{g}_{\mu\nu} = \bar{f}_{\mu\nu} = \mathrm{FRW}$$

Scalar sector

$$\phi_g = \bar{\phi}_g + \varphi_g$$

$$\phi_f = \bar{\phi}_f + \varphi_f$$

$$\frac{1}{M_g}\,\bar{\phi}_g = \frac{1}{M_f}\,\bar{\phi}_f \equiv \frac{1}{M_P}\,\bar{\phi}$$

$$\frac{1}{M_g^2}\,V_g\left(\tfrac{M_g}{M_P}\phi\right) = \frac{1}{M_f^2}\,V_f\left(\tfrac{M_f}{M_P}\phi\right) \equiv \frac{1}{M_P}\,V(\phi)$$

Background EoMs:

$$\bar{R}_{\mu\nu} - \frac{1}{2}\bar{g}_{\mu\nu}\bar{R} = \frac{1}{M_P^2}\,\bar{T}_{\mu\nu}$$

$$\Box\bar{\phi} - V'(\bar{\phi}) = 0$$

$$\bar{T}_{\mu\nu} = \nabla_\mu\bar{\phi}\nabla_\nu\bar{\phi} + \bar{g}_{\mu\nu}\bar{\mathcal{L}}(\bar{g},\bar{\phi})$$

$$\bar{\mathcal{L}}(\bar{g},\bar{\phi}) = -\tfrac{1}{2}\bar{g}^{\mu\nu}\nabla_\mu\bar{\phi}\nabla_\nu\bar{\phi} - V(\bar{\phi})$$

Change Perturbation Variables to Mass Eigenstates

$$\{h_{\mu\nu},\ k_{\mu\nu}\} \to \{u_{\mu\nu},\ v_{\mu\nu}\}$$

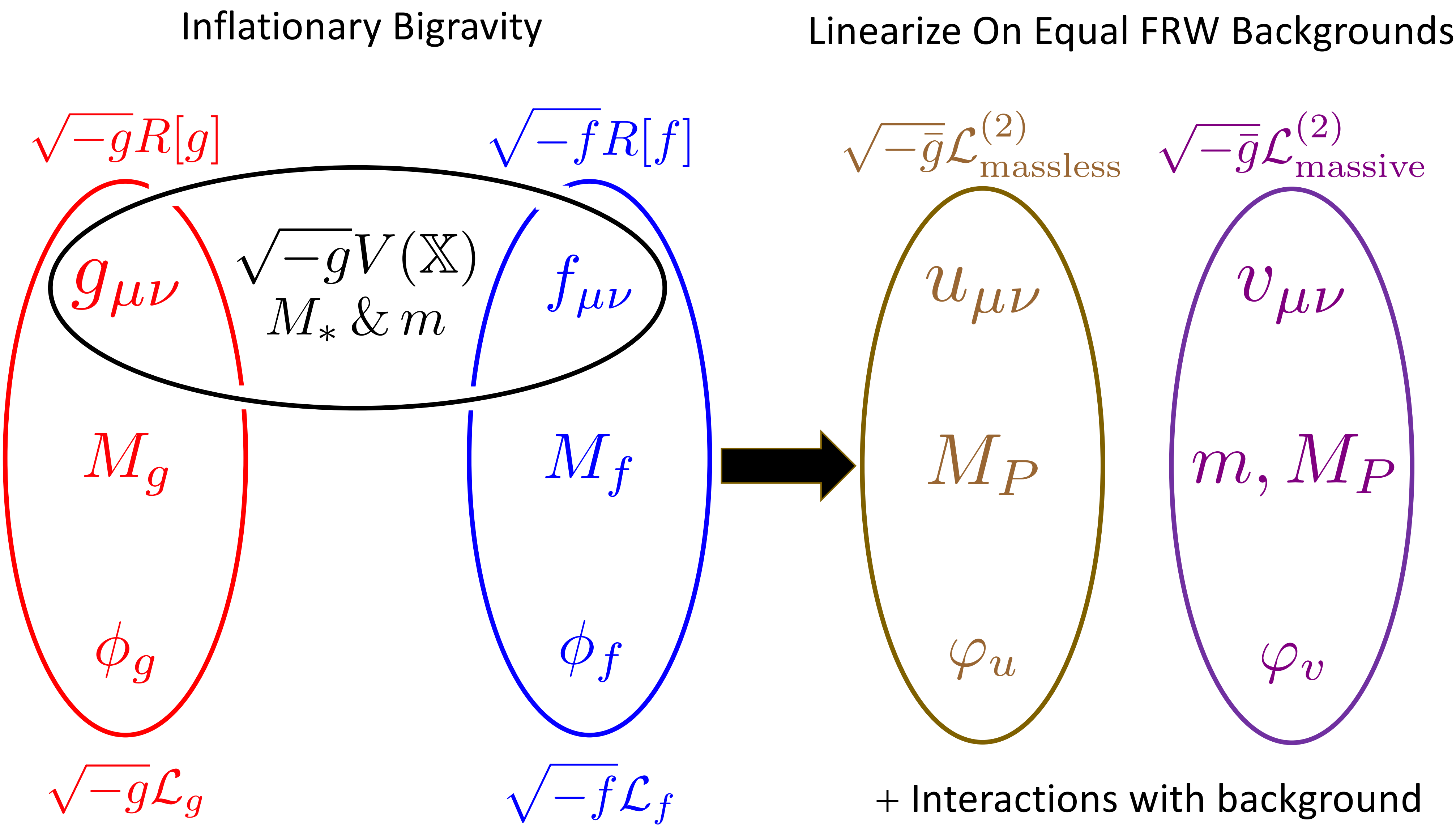
$$\frac{u_{\mu\nu}}{M_*} = \frac{h_{\mu\nu}}{M_f} + \frac{k_{\mu\nu}}{M_g}$$

$$\frac{v_{\mu\nu}}{M_*} = \frac{h_{\mu\nu}}{M_g} - \frac{k_{\mu\nu}}{M_f}$$

$$\{\varphi_g,\ \varphi_f\} \to \{\varphi_u,\ \varphi_v\}$$

$$\frac{\varphi_u}{M_*} = \frac{\varphi_g}{M_f} + \frac{\varphi_f}{M_g}$$

$$\frac{\varphi_v}{M_*} = \frac{\varphi_g}{M_g} - \frac{\varphi_f}{M_f}$$


Inflationary Bigravity
Linearize On Equal FRW Backgrounds
$\sqrt{-g}R[g]$
$\sqrt{-f}R[f]$
$\sqrt{-g}V(\mathbb{X})$
$M_* \,\&\, m$
$g_{\mu\nu}$
$f_{\mu\nu}$
M_g
M_f
ϕ_g
ϕ_f
$\sqrt{-g}\mathcal{L}_g$
$\sqrt{-f}\mathcal{L}_f$
$\sqrt{-\bar{g}}\mathcal{L}^{(2)}_{\text{massless}}$
$\sqrt{-\bar{g}}\mathcal{L}^{(2)}_{\text{massive}}$
$u_{\mu\nu}$
$v_{\mu\nu}$
M_P
m, M_P
φ_u
φ_v
+ Interactions with background

Change Perturbation Variables: Massive and Massless Modes Decouple

$$\mathcal{L}^{(2)}_{\text{massless}} = \mathcal{L}^{(2)}_{uu} + \mathcal{L}^{(2)}_{u\varphi_u} + \mathcal{L}^{(2)}_{\varphi_u\varphi_u}$$

$$\begin{aligned}\mathcal{L}^{(2)}_{uu} =& -\tfrac{1}{2}\nabla_\lambda u_{\mu\nu}\nabla^\lambda u^{\mu\nu} + \nabla_\mu u^{\nu\lambda}\nabla_\nu u^\mu{}_\lambda \\ & - \nabla_\mu u^{\mu\nu}\nabla_\nu u + \tfrac{1}{2}\nabla_\mu u\nabla^\mu u \\ & + \left(\bar{R}_{\mu\nu} - M_P^{-2}\,\nabla_\mu\bar{\phi}\nabla_\nu\bar{\phi}\right) \\ & \times \left(u^{\mu\lambda}u_\lambda{}^\nu - \tfrac{1}{2}u^{\mu\nu}u\right)\end{aligned}$$

$$\begin{aligned}\mathcal{L}^{(2)}_{u\,\varphi_u} =& M_P^{-1}\Big[\left(\nabla_\mu\bar{\phi}\nabla_\nu\varphi_u + \nabla_\nu\bar{\phi}\nabla_\mu\varphi_u\right) \\ & \times \left(u^{\mu\nu} - \tfrac{1}{2}\bar{g}^{\mu\nu}u\right) - V'(\bar{\phi})\varphi_u u\Big]\end{aligned}$$

$$\mathcal{L}^{(2)}_{\varphi_u\varphi_u} = -\tfrac{1}{2}\nabla_\mu\varphi_u\nabla^\mu\varphi_u - \tfrac{1}{2}V''(\bar{\phi})\varphi_u^2$$

$$\mathcal{L}^{(2)}_{\text{massive}} = \mathcal{L}^{(2)}_{vv} + \mathcal{L}^{(2)}_{v\varphi_v} + \mathcal{L}^{(2)}_{\varphi_v\varphi_v}$$

$$\begin{aligned}\mathcal{L}^{(2)}_{vv} =& -\tfrac{1}{2}\nabla_\lambda v_{\mu\nu}\nabla^\lambda v^{\mu\nu} + \nabla_\mu v^{\nu\lambda}\nabla_\nu v^\mu{}_\lambda \\ & - \nabla_\mu v^{\mu\nu}\nabla_\nu v + \tfrac{1}{2}\nabla_\mu v\nabla^\mu v \\ & + \left(\bar{R}_{\mu\nu} - M_P^{-2}\,\nabla_\mu\bar{\phi}\nabla_\nu\bar{\phi}\right) \\ & \times \left(v^{\mu\lambda}v_\lambda{}^\nu - \tfrac{1}{2}v^{\mu\nu}v\right) \\ & \boxed{-\tfrac{1}{2}m^2\left(v^{\mu\nu}v_{\mu\nu} - v^2\right)}\end{aligned}$$

$$\begin{aligned}\mathcal{L}^{(2)}_{v\,\varphi_v} =& M_P^{-1}\Big[\left(\nabla_\mu\bar{\phi}\nabla_\nu\varphi_v + \nabla_\nu\bar{\phi}\nabla_\mu\varphi_v\right) \\ & \times \left(v^{\mu\nu} - \tfrac{1}{2}\bar{g}^{\mu\nu}v\right) - V'(\bar{\phi})\varphi_v v\Big]\end{aligned}$$

$$\mathcal{L}^{(2)}_{\varphi_v\varphi_v} = -\tfrac{1}{2}\nabla_\mu\varphi_v\nabla^\mu\varphi_v - \tfrac{1}{2}V''(\bar{\phi})\varphi_v^2$$

Scalar/Vector/Tensor (SVT) Decomposition Of Massive Spin-2 Field

Represent 4-tensor by variables that transform under spatial rotations as 3–scalars/3–vectors/3–tensors

$$v_{00} = a^2 E \qquad v_{0i} = a^2 (\partial_i F + G_i) \qquad v_{ij} = a^2 (\delta_{ij} A + \partial_i \partial_j B + \partial_i C_j + \partial_j C_i + D_{ij})$$

Subject to transverse/traceless constraints (repeated indices summed):

$$\partial_i C_i = 0, \quad \partial_i G_i = 0, \quad \partial_i D_{ij} = 0, \quad \text{and} \quad D_{ii} = 0$$

At quadratic order S/V/T decouple: $d\eta = dt/a(t)$

$$S = \int d\eta \, d^3x \, \left(L_S + L_V + L_T\right) + \mathcal{O}^3$$

(Set your watch to CST—Conformal Standard Time)

For S/V/T

1. Remove nondynamical DoFs.
2. Express in terms of Fourier modes.
3. Canonically normalize kinetic term.
4. Check for ghosts, gradient instabilities.
5. Find mode equation and ω_k: $\tilde{\psi}'' + \omega_k^2 \tilde{\psi} = 0$.
6. Solve with appropriate boundary conditions.
7. Integrate over k.
8. Write paper.

Tensor Sector (Prime Denotes ∂_η)

$$L_T = \frac{1}{2}a^2\left[D'_{ij}D'_{ij} - \partial_k D_{ij}\partial_k D_{ij} - a^2m^2D_{ij}D_{ij}\right]$$

Canonically normalized kinetic term: $\chi_{ij} = aD_{ij}$

Fourier modes of $\chi_{ij}(\eta,\mathbf{x}) \equiv \tilde{\chi}_{ij}(\eta,\mathbf{k})$; can take $\mathbf{k} = (0,0,k)$

$$[\tilde{\chi}_{ij}] = \begin{bmatrix} \tilde{\chi}_+ & \tilde{\chi}_\times & 0 \\ \tilde{\chi}_\times & -\tilde{\chi}_+ & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\tilde{\chi}''_{\substack{+\\ \times}}(\eta,k) + \omega_k^2(\eta)\,\tilde{\chi}_{\substack{+\\ \times}}(\eta,k) = 0$$

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

If $m=0$, mode equation for gravitational wave propagating on an FRW background, familiar from studies of tensor perturbations in inflation

Vector Sector (Prime Denotes ∂_η)

$$L_V = a^2\Big[\partial_j\big(G_i - C_i'\big)\partial_j\big(G_i - C_i'\big) + a^2 m^2\big(G_i G_j - \partial_j C_i \partial_j C_i\big)\Big]$$

G_i not dynamical,
can be Integrated out

In Fourier space: $$L_{V,k} = \frac{a^4 k^2 m^2}{k^2 + a^2 m^2}|\tilde{C}_i'|^2 - a^4 k^2 m^2 |\tilde{C}_i|^2$$

If $m = 0$, Lagrangian vanishes trivially since massless theory does not propagate vector modes.

Canonically normalize, again taking $\mathbf{k} = (0,0,k)$, and defining $\tilde{\chi}_\pm(\eta, k) = (\tilde{\chi}_1 \mp i\tilde{\chi}_2)/\sqrt{2}$:

$$\begin{aligned}
\tilde{\chi}_\pm''(\eta,k) + \omega_k^2(\eta)\,\tilde{\chi}_\pm(\eta,k) &= 0 \\
\omega_k^2(\eta) &= k^2 + a^2 m^2 - f''/f \\
f &= a^2/\sqrt{k^2 + a^2 m^2}
\end{aligned}$$

Scalar Sector (Prime Denotes ∂_η)

$L_S = L_S(A, B, E, F, \varphi_v)$ (and φ_u decoupled).

After removing non-propagating DoFs, and defining $\hat{\varphi}_v = \varphi_v - \dfrac{a^{-1}\bar{\phi}'}{M_P H} A$

$$L_{S,k} = K_\varphi \, |\tilde{\hat{\varphi}}_v'|^2 - M_\varphi \, |\tilde{\hat{\varphi}}_v|^2 + K_B \, |\tilde{B}'|^2 - M_B \, |\tilde{B}|^2 + L_2 \, \tilde{\hat{\varphi}}_v^{*\prime} \tilde{B}' + L_1 \, \tilde{\hat{\varphi}}_v^{*} \tilde{B}' - L_0 \, \tilde{\hat{\varphi}}_v^{*} \tilde{B}$$

$$L_{S,k} = K_\varphi \, |\tilde{\hat{\varphi}}_v'|^2 - M_\varphi \, |\tilde{\hat{\varphi}}_v|^2 + K_B \, |\tilde{B}'|^2 - M_B \, |\tilde{B}|^2 + L_2 \, \tilde{\hat{\varphi}}_v^{*\prime} \tilde{B}' + L_1 \, \tilde{\hat{\varphi}}_v^{*} \tilde{B}' - L_0 \, \tilde{\hat{\varphi}}_v^{*} \tilde{B}$$

$$K_B = \frac{a^6 m^2}{8} \frac{\left(8m^2H^2 - 6H^2m_H^2 - m^2m_H^2\right)k^4}{H^2k^4 + 3a^2\left(m^2 - m_H^2\right)H^2k^2 + \frac{3}{8}a^4m^2\left(6m^2H^2 - 4H^2m_H^2 - m_H^4\right)} \tag{3.17c}$$

$$M_B = \frac{a^6 m^2}{8} \frac{c_{10}k^{10} + c_8k^8 + c_6k^6 + c_4k^4}{\left[H^2k^4 + 3a^2\left(m^2 - m_H^2\right)H^2k^2 + \frac{3}{8}a^4m^2\left(6m^2H^2 - 4H^2m_H^2 - m_H^4\right)\right]^2} \tag{3.17d}$$

$$\begin{aligned}
c_{10} &= H^2\left(8m^2H^2 - 8H^4 - 2H^2m_H^2 - m^2m_H^2\right) \\
c_8 &= a^2H^2\Big[\big(30m^4H^2 + 32m^2H^4 - 96H^6 - 3m^4m_H^2 - 56m^2H^2m_H^2 \\
&\qquad + 48H^4m_H^2 + 5m^2m_H^4 + 6H^2m_H^4\big) \\
&\qquad + \left(4m^2 - 24H^2\right)\tfrac{HV'(\bar\phi)\bar\phi'}{aM_P^2}\Big] \\
c_6 &= \tfrac{3}{8}a^4m^2\Big[\big(96m^4H^4 + 144m^2H^6 - 6m^4H^2m_H^2 - 252m^2H^4m_H^2 - 192H^6m_H^2 \\
&\qquad + 8m^2H^2m_H^4 + 200H^4m_H^4 - 10H^2m_H^6 - m^2m_H^6\big) \\
&\qquad + \left(8m^2m_H^2 - 16H^2m_H^2\right)\tfrac{HV'(\bar\phi)\bar\phi'}{aM_P^2}\Big] \\
c_4 &= \tfrac{3}{8}a^6m^4\Big[\big(36m^4H^4 - 48m^2H^6 + 64H^8 - 12m^2H^4m_H^2 - 32H^6m_H^2 \\
&\qquad - 12m^2H^2m_H^4 + 4H^4m_H^4 + 12H^2m_H^6 - 3m^2m_H^6 + 2m_H^8\big) \\
&\qquad - \left(24m^2H^2 - 16H^4 - 12m^2m_H^2 - 8H^2m_H^2 + 8m_H^4\right)\tfrac{HV'(\bar\phi)\bar\phi'}{aM_P^2}\Big]
\end{aligned}$$

$$L_2 = \frac{a^3m^2\bar\phi'}{2M_PH} \frac{H^2k^4 + \frac{3}{2}a^2\left(m^2 - m_H^2\right)H^2k^2}{H^2k^4 + 3a^2\left(m^2 - m_H^2\right)H^2k^2 + \frac{3}{8}a^4m^2\left(6m^2H^2 - 4H^2m_H^2 - m_H^4\right)} \tag{3.17e}$$

$$L_1 = -\frac{a^4m^2\bar\phi'}{M_P} \frac{\left(H^2 - \frac{1}{4}m_H^2 - \frac{1}{2}\frac{aHV'(\bar\phi)}{\bar\phi'}\right)k^4 - \frac{3}{2}a^2\left(m^2 - m_H^2\right)\left(H^2 + \frac{1}{4}m_H^2 + \frac{1}{2}\frac{aHV'(\bar\phi)}{\bar\phi'}\right)k^2}{H^2k^4 + 3a^2\left(m^2 - m_H^2\right)H^2k^2 + \frac{3}{8}a^4m^2\left(6m^2H^2 - 4H^2m_H^2 - m_H^4\right)} \tag{3.17f}$$

$$L_0 = \frac{a^3m^2\bar\phi'}{2M_PH} \frac{c_{10}k^{10} + c_8k^8 + c_6k^6 + c_4k^4 + c_2k^2}{\left[H^2k^4 + 3a^2\left(m^2 - m_H^2\right)H^2k^2 + \frac{3}{8}a^4m^2\left(6m^2H^2 - 4H^2m_H^2 - m_H^4\right)\right]^2} \tag{3.17g}$$

$$c_{10} = H^4 \tag{3.17h}$$

$$\begin{aligned}
c_8 &= \tfrac{1}{2}a^2H^4\Big[\left(9m^2 + 12H^2 - 13m_H^2\right) - 4\tfrac{aHV'(\bar\phi)}{\bar\phi'}\Big] \\
c_6 &= \tfrac{3}{8}a^4H^2\Big[\big(18m^4H^2 + 32m^2H^4 + 64H^6 - 48m^2H^2m_H^2 - 64H^4m_H^2 \\
&\qquad + m^2m_H^4 + 28H^2m_H^4\big) \\
&\qquad + 8\left(-4m^2H^2 + 4H^4 + m^2m_H^2\right)\tfrac{aHV'(\bar\phi)}{\bar\phi'}\Big] \\
c_4 &= \tfrac{3}{16}a^6m^2H^2\Big[\big(18m^4H^2 - 24m^2H^4 + 256H^6 - 54m^2H^2m_H^2 - 160H^4m_H^2 \\
&\qquad + 9m^2m_H^4 + 60H^2m_H^4 - 7m_H^6\big) \\
&\qquad + 4\left(-30m^2H^2 + 32H^4 + 12m^2m_H^2 + 4H^2m_H^2 - 7m_H^4\right)\tfrac{aHV'(\bar\phi)}{\bar\phi'}\Big] \\
c_2 &= \tfrac{9}{16}a^8m^4H^2\left(2H^2 - m_H^2\right)\Big[-\left(4H^2 + m_H^2\right)\left(3m^2 - 4H^2 - m_H^2\right) \\
&\qquad + 4\left(-3m^2 + 2H^2 + 2m_H^2\right)\tfrac{aHV'(\bar\phi)}{\bar\phi'}\Big]
\end{aligned}$$

$$K_\varphi = \frac{a^2}{2} \frac{H^2k^4 + 3a^2\left(m^2 - m_H^2\right)H^2k^2 + \frac{9}{4}a^4m^2\left(m^2 - m_H^2\right)H^2}{H^2k^4 + 3a^2\left(m^2 - m_H^2\right)H^2k^2 + \frac{3}{8}a^4m^2\left(6m^2H^2 - 4H^2m_H^2 - m_H^4\right)} \tag{3.17a}$$

$$M_\varphi = \frac{a^2}{2} \frac{c_{10}k^{10} + c_8k^8 + c_6k^6 + c_4k^4 + c_2k^2 + c_0}{\left[H^2k^4 + 3a^2\left(m^2 - m_H^2\right)H^2k^2 + \frac{3}{8}a^4m^2\left(6m^2H^2 - 4H^2m_H^2 - m_H^4\right)\right]^2} \tag{3.17b}$$

$$\begin{aligned}
c_{10} &= H^4 \\
c_8 &= \tfrac{1}{2}a^2H^2\Big[\left(12m^2H^2 + 8H^4 - 14H^2m_H^2 - m_H^4\right) + 4\tfrac{HV'(\bar\phi)\bar\phi'}{aM_P^2} + 2H^2V''(\bar\phi)\Big] \\
c_6 &= \tfrac{3}{8}a^4H^2\Big[\big(36m^4H^2 + 72m^2H^4 - 82m^2H^2m_H^2 - 64H^4m_H^2 \\
&\qquad - 7m^2m_H^4 + 40H^2m_H^4 + 8m_H^6\big) \\
&\qquad + 8\left(3m^2 - 4m_H^2\right)\tfrac{HV'(\bar\phi)\bar\phi'}{aM_P^2} \\
&\qquad + 16\left(m^2 - m_H^2\right)H^2V''(\bar\phi)\Big] \\
c_4 &= \tfrac{3}{8}a^6\Big[4H^2\big(9m^6H^2 + 36m^4H^4 + 16m^2H^6 - 30m^4H^2m_H^2 - 76m^2H^4m_H^2 \\
&\qquad - 3m^4m_H^4 + 31m^2H^2m_H^4 + 24H^4m_H^4 + 6m^2m_H^6 - 6H^2m_H^6 - 3m_H^8\big) \\
&\qquad - 4m^2H^2\left(H^2 - m_H^2\right)\tfrac{V'(\bar\phi)^2}{M_P^2} \\
&\qquad + \left(36m^4H^2 + 8m^2H^4 - 94m^2H^2m_H^2 + m^2m_H^4 + 48H^2m_H^4\right)\tfrac{HV'(\bar\phi)\bar\phi'}{aM_P^2} \\
&\qquad + \left(36m^4H^2 - 58m^2H^2m_H^2 - m^2m_H^4 + 24H^2m_H^4\right)H^2V''(\bar\phi)\Big] \\
c_2 &= \tfrac{9}{32}a^8m^2\Big[H^2\big(18m^6H^2 + 120m^4H^4 + 128m^2H^6 - 78m^4H^2m_H^2 - 384m^2H^4m_H^2 \\
&\qquad - 9m^4m_H^4 + 132m^2H^2m_H^4 + 128H^4m_H^4 + 23m^2m_H^6 - 32H^2m_H^6 - 16m_H^8\big) \\
&\qquad - 8H^2\left(2m^2H^2 - 2m^2m_H^2 + m_H^4\right)\tfrac{V'(\bar\phi)^2}{M_P^2} \\
&\qquad + 4\left(6m^4H^2 - 22m^2H^2m_H^2 + m^2m_H^4 + 14H^2m_H^4\right)\tfrac{HV'(\bar\phi)\bar\phi'}{aM_P^2} \\
&\qquad + 4\left(m^2 - m_H^2\right)\left(12m^2H^2 - 10H^2m_H^2 - m_H^4\right)H^2V''(\bar\phi)\Big] \\
c_0 &= \tfrac{27}{32}a^{10}m^4\Big[-2H^2\left(2m^2H^2 - 2m^2m_H^2 + m_H^4\right)\tfrac{V'(\bar\phi)^2}{M_P^2} \\
&\qquad - m^2\left(2H^2 - m_H^2\right)\left(4H^2 + m_H^2\right)\tfrac{HV'(\bar\phi)\bar\phi'}{aM_P^2} \\
&\qquad + \left(m^2 - m_H^2\right)\left(6m^2H^2 - 4H^2m_H^2 - m_H^4\right)H^2V''(\bar\phi)\Big]
\end{aligned}$$

$$\boxed{\text{Why you might not wish to do this!}}$$

Scalar Sector (Prime Denotes ∂_η)

$L_S = L_S(A, B, E, F, \varphi_v)$ (and φ_u decoupled).

After removing non-propagating DoFs, and defining $\hat{\varphi}_v = \varphi_v - \frac{a^{-1}\bar{\phi}'}{M_P H} A$

$$L_{S,k} = K_\varphi\, |\tilde{\hat{\varphi}}_v'|^2 - M_\varphi\, |\tilde{\hat{\varphi}}_v|^2 + K_B\, |\tilde{B}'|^2 - M_B\, |\tilde{B}|^2 + L_2\, \tilde{\hat{\varphi}}_v^{*\prime} \tilde{B}' + L_1\, \tilde{\hat{\varphi}}_v^{*} \tilde{B}' - L_0\, \tilde{\hat{\varphi}}_v^{*} \tilde{B}$$

Yet another Field redefinition to diagonalize kinetic terms: $\{\tilde{\hat{\varphi}}_v, \tilde{B}\} \Rightarrow \{\tilde{\Pi}, \tilde{\mathcal{B}}\}$

$$L_{S,k} = K_\Pi\, |\tilde{\Pi}'|^2 - M_\Pi\, |\tilde{\Pi}|^2 + K_{\mathcal{B}}\, |\tilde{\mathcal{B}}'|^2 - M_{\mathcal{B}}\, |\tilde{\mathcal{B}}|^2 + \lambda_1\, \tilde{\Pi}^* \tilde{\mathcal{B}}' - \lambda_0\, \tilde{\Pi}^* \tilde{\mathcal{B}}$$

Scalar Sector (Prime Denotes ∂_η)

$$K_\Pi = \frac{a^2}{2}\frac{H^2k^4 + 3a^2\big(m^2 - m_H^2\big)H^2k^2 + \frac{9}{4}a^4m^2\big(m^2 - m_H^2\big)H^2}{H^2k^4 + 3a^2\big(m^2 - m_H^2\big)H^2k^2 + \frac{3}{8}a^4m^2\big(6m^2H^2 - 4H^2m_H^2 - m_H^4\big)}$$

$$K_{\mathcal{B}} = \frac{3a^6m^2(m^2 - m_H^2)}{4k^4 + 12a^2(m^2 - m_H^2)k^2 + 9a^4m^2(m^2 - m_H^2)}$$

Where we have defined $m_H^2(\eta) = 2H^2(\eta)\big[1 - \epsilon(\eta)\big]$ $\epsilon(\eta) = -H'/(aH^2)$

ϵ is the first inflationary slow-roll parameter.

If $m < m_H(\eta)$, theory propagates a ghost in $\tilde{\mathcal{B}}$ (spin–2) sector!

Generalized Higuchi Bound

In 1986 Higuchi studied perturbations of massive gravity on a de Sitter background and found a ghost if $m^2 < 2H^2$.

In dS, $m^2 = 2\,H^2$ is a “partially massless” point: mass term also vanishes.

We find a ghost in a general FRW background if $m^2 < 2H^2(\eta)\,[\,1 - \epsilon(\eta)\,]$. (In dS $\epsilon = 0$.)

FRW ghost is not generally a “partially massless” point.

Question For My Wise Colleagues

How should one regard a theory, perfectly healthy in Minkowski spacetime, but ghostly in a non-pathological, classical gravitational background?

In FRW, $m^2 > 2H^2(\eta)[1-\varepsilon(\eta)]$ to avoid ghosts.

In principle, H could be anything!

Scalar Sector (Prime Denotes ∂_η)

$$L_{S,k} = K_\Pi\,|\tilde{\Pi}'|^2 - M_\Pi\,|\tilde{\Pi}|^2 + K_{\mathcal{B}}\,|\tilde{\mathcal{B}}'|^2 - M_{\mathcal{B}}\,|\tilde{\mathcal{B}}|^2 + \lambda_1\,\tilde{\Pi}^*\tilde{\mathcal{B}}' - \lambda_0\,\tilde{\Pi}^*\tilde{\mathcal{B}}$$

<u>At late times:</u>

$$L_{S,k} = \underbrace{\frac{1}{2}\Big[|\tilde{\chi}'_\Pi|^2 - \big(k^2 + a^2 V''(\bar{\phi})\big)|\tilde{\chi}_\Pi|^2\Big]}_{\text{Inflaton DoF}} + \underbrace{\frac{1}{2}\Big[|\tilde{\chi}'_{\mathcal{B}}|^2 - \big(k^2 + a^2 m^2\big)|\tilde{\chi}_{\mathcal{B}}|^2\Big]}_{\text{Massive spin-2 DoF}} + \mathcal{O}(H/m)$$

CGPP (Finally!)

Have mode equations for $u_{\mu\nu}$(tensor) , $\boldsymbol{\varphi}_u$, $v_{\mu\nu}$(tensor, vector) , Π , $\mathcal{B}$

No DoF left behind: $2 \quad + \; 1 \; + \quad 2 \quad + \; 2 \quad +1 + 1 \; = \; 9$

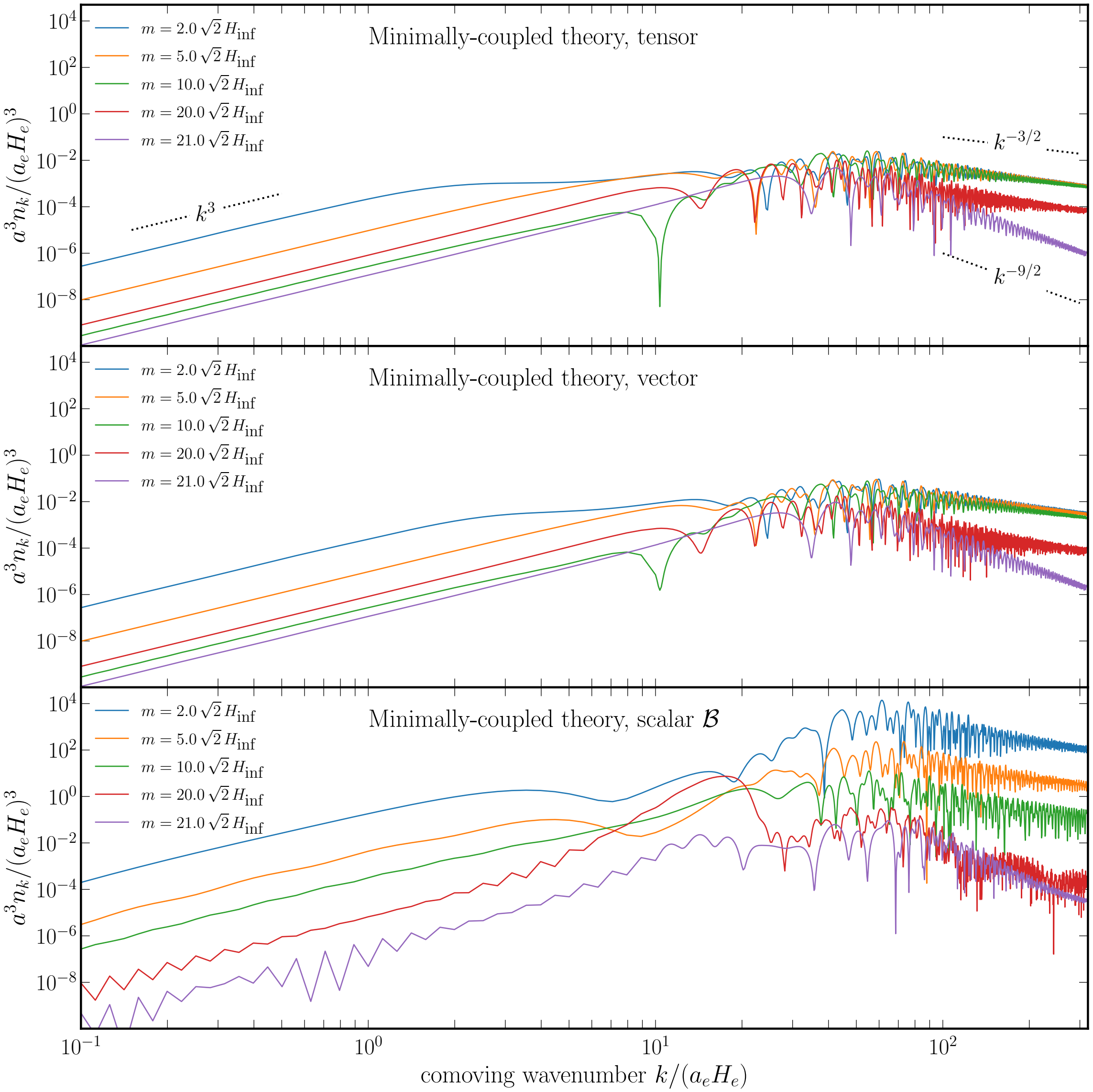
1. Mode equation: $\tilde{\psi}''(\eta, k) + \omega_k^2(\eta)\tilde{\psi}(\eta, k) = 0$
2. Bunch-Davies (Minkowski) initial conditions: $\lim\limits_{\eta\to-\infty} \tilde{\psi}(\eta, k) = \dfrac{1}{\sqrt{2k}}\, e^{-ik\eta}$
3. Calculate $\tilde{\psi}$ at late time when mode is
    - nonrelativistic
    - subhorizon
    - evolution approximately adiabatic
4. Calculate Bogolubov coefficient for modes with wavenumber k

$$|\beta_k|^2 = \lim_{\eta\to\infty} \left(\frac{\omega_k}{2}|\tilde{\psi}|^2 + \frac{1}{2\omega_k}|\partial_\eta \tilde{\psi}|^2 - \frac{1}{2} \right)$$

5. Physical number density of particles with comoving momentum $p = k$

$$n_k(\eta) = a^{-3}(\eta)\frac{k^3}{2\pi^2}|\beta_k|^2$$

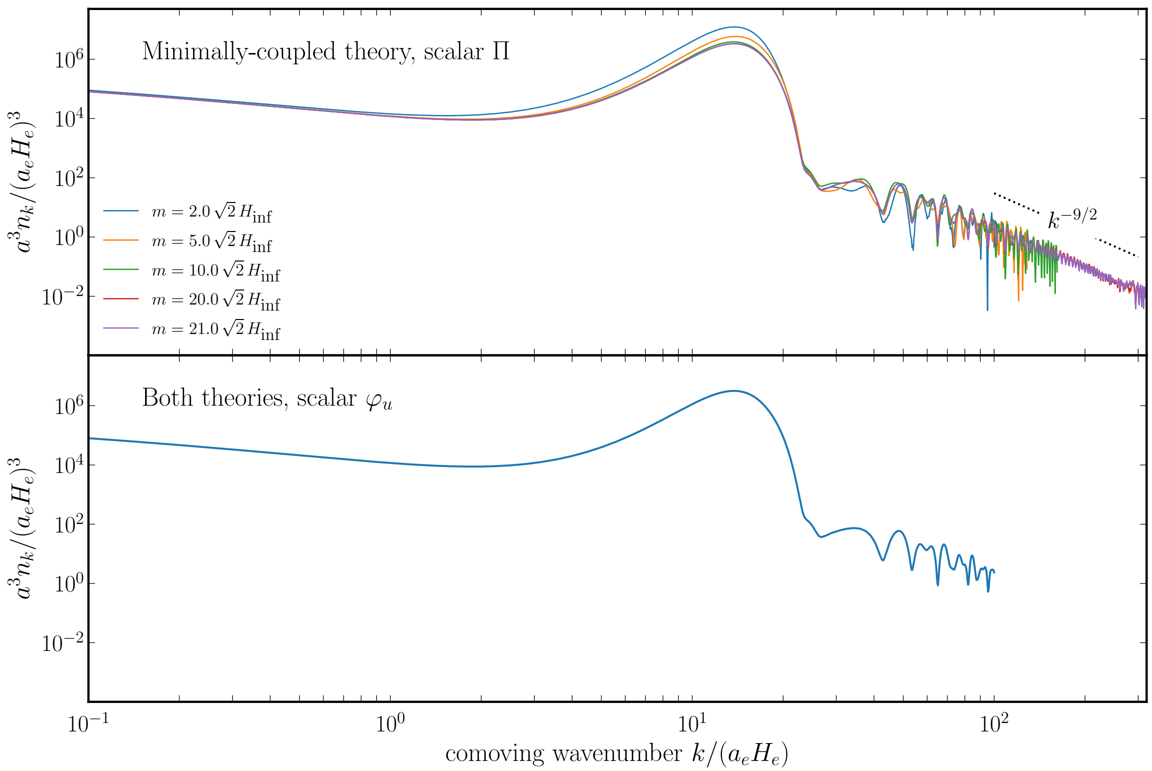
Total number density: $n(\eta) = \int \frac{dk}{k} n_k(\eta)$



Massive Spin–2 Spectra

- Modes with $k/a_e H_e < 1$ left horizon before end of inflation
- Modes with $k/a_e H_e > 1$ always sub-horizon
- Only consider non-ghostly masses
- Low-k oscillations explained
- High-k oscillations explained
  Basso, Chung, EWK, Long 2209.01713
- Low-k scaling (k^3) explained
- High-k scaling ($k^{-3/2}$ or $k^{-9/2}$) explained
  Basso, Chung, EWK, Long 2209.01713
- Scalar (helicity-0 mode) dominates

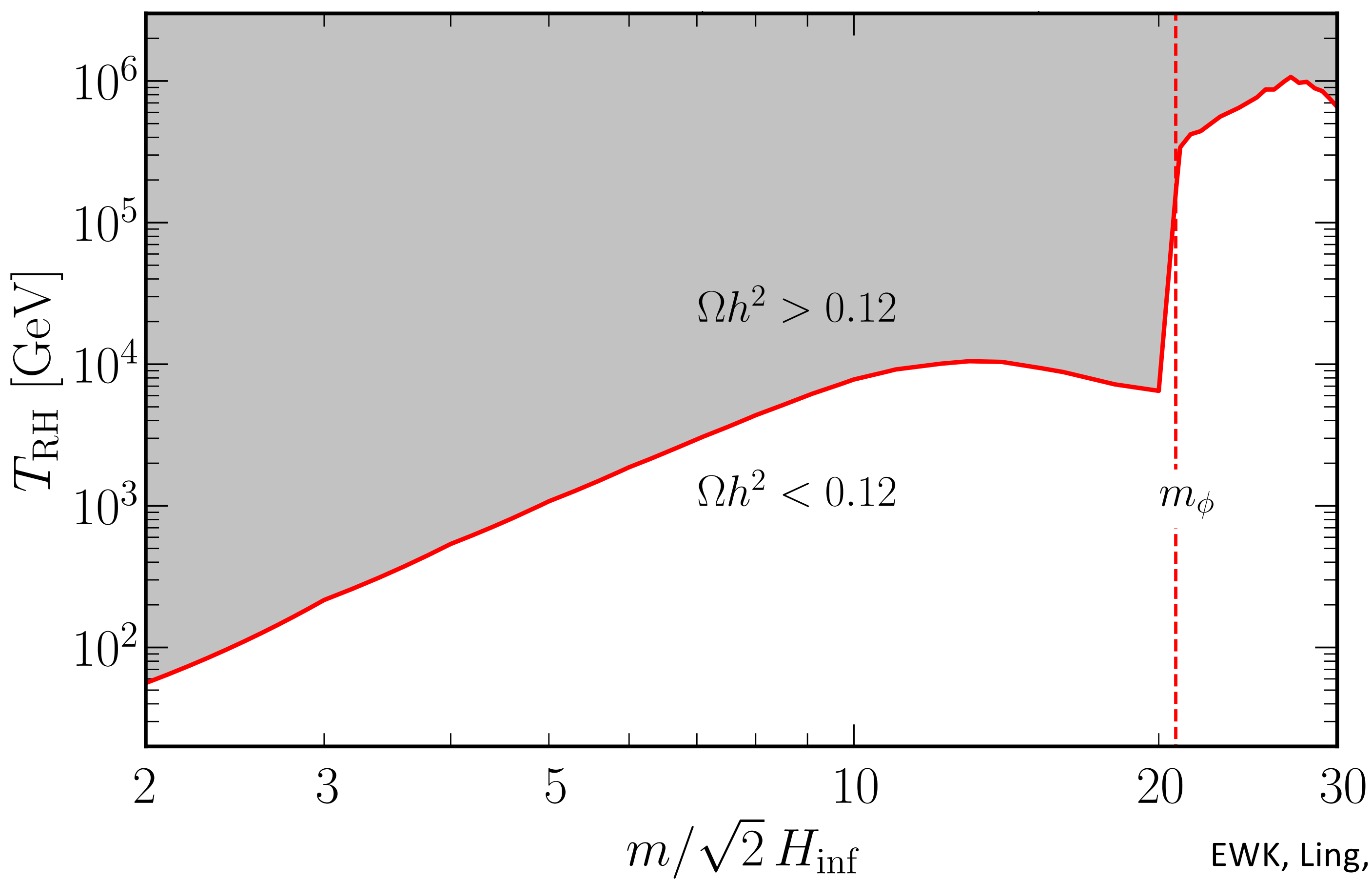
Inflaton Spectra



- Modes with $k/a_e H_e < 1$ left horizon before end of inflation
- Modes with $k/a_e H_e > 1$ always sub-horizon
- Only consider non-ghostly Π masses
- High-k oscillations explained
  Basso, Chung, EWK, Long 2209.01713
- Low-k scaling explained
- High-k scaling ($k^{-9/2}$) explained
  Basso, Chung, EWK, Long 2209.01713

Massive Bigravity

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



EWK, Ling, Long, Rosen (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 $m \lesssim$ few H_e.

If allow $2\times10^{-2} \lesssim \xi \lesssim 10^2$ 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 ($\mu\mathrm{eV}$) 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

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.

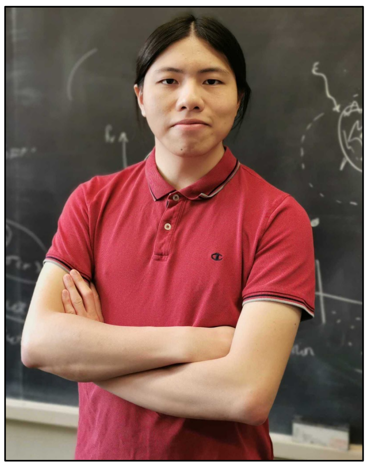
Thanks to my collaborators in 25 years of CGPP: (Chung, EWK, Riotto, *PRD* **59** (1998) 023501)

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

Cosmological Gravitational Particle Production of Massive Spin-2 Particles [2302.04390; JHEP 05 (2023) 181]

Collaborators:

Siyang Ling



Grad Student
Rice

Andrew Long

Faculty
Rice

Rachel Rosen

Faculty
Carnegie-Mellon

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. CDM.
- “Detectable” by direct detection, indirect detection, decay products, production at colliders
- Just BSM, e.g., low-energy SUSY!

The WIMP "Miracle"

Merriam-Webster

Merriam-Webster OnLine

mir·a·cle
\ˈmir-i-kəl \
noun

1 : an extraordinary event manifesting divine intervention in human affairs

Miracle

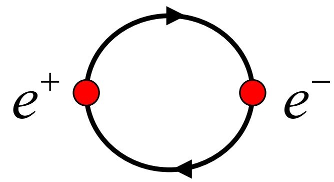
From Wikipedia, the free encyclopedia

… often used to give an impression of great and unusual value in a trivial context …

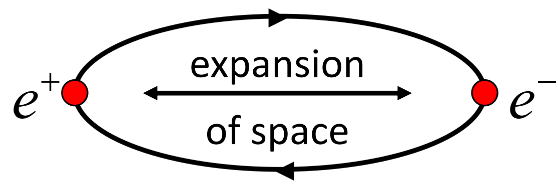
WIKIPEDIA
The Free Encyclopedia

Produce Dark Matter from Expansion of the Universe

Expanding universe $\longrightarrow$ Particle creation



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



$\mathrm{v} = c$ at Hubble radius

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

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

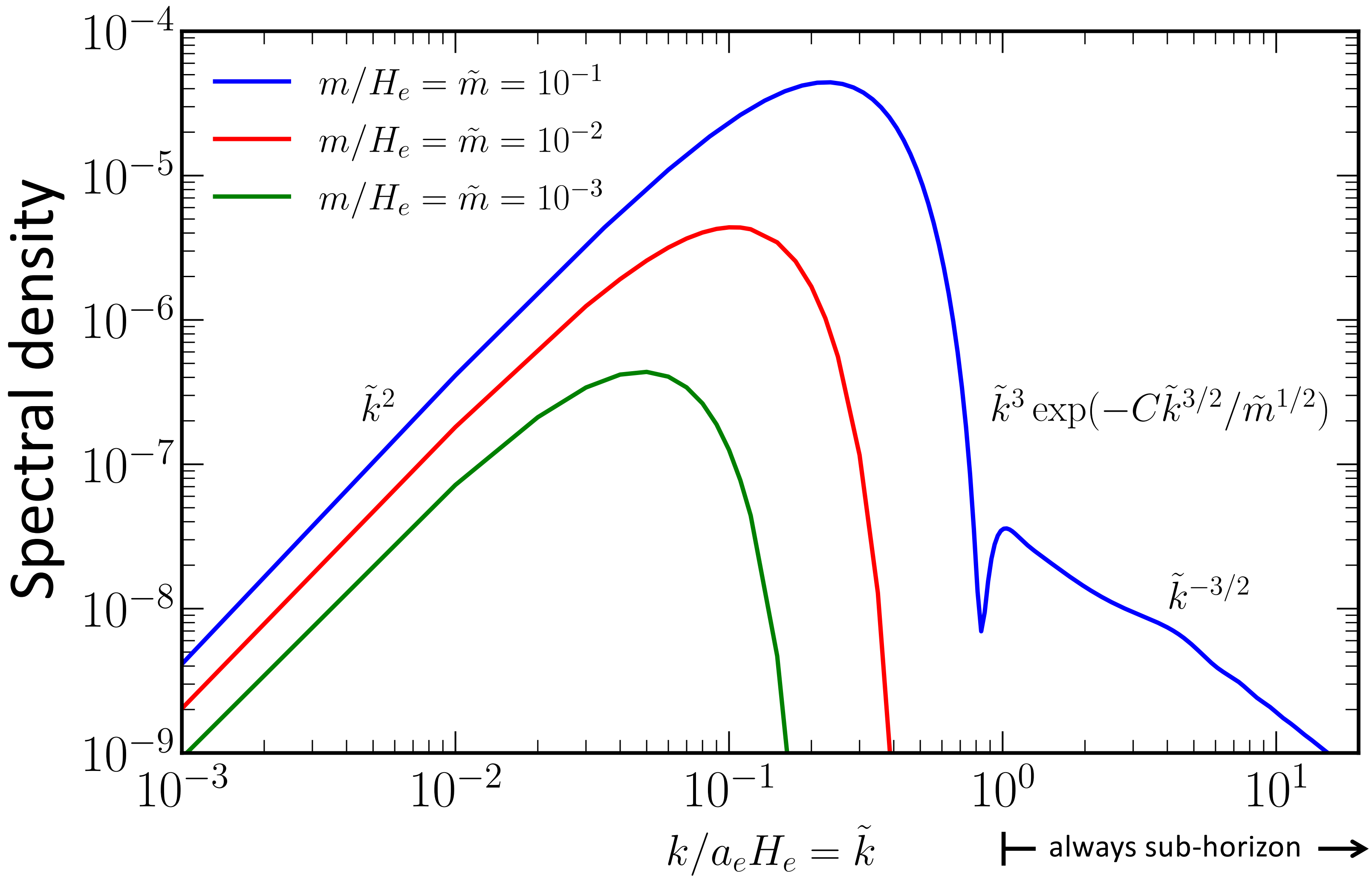
$$\chi_k(\eta) = \frac{\alpha_k(\eta)}{\sqrt{2\omega_k(\eta)}}\, e^{-i\int \omega_k(\eta) d\eta} - \frac{\beta_k(\eta)}{\sqrt{2\omega_k(\eta)}}\, e^{+i\int \omega_k(\eta) d\eta} \qquad |\alpha_k|^2 - |\beta_k|^2 = 1$$

If start with only positive frequency modes, $|\alpha_k| = 1$ & $|\beta_k| = 0$,
Expansion of the universe will generate negative frequency modes (particles), $\beta_k \neq 0$.

<u>Comoving</u> number density of particles at late time is

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

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



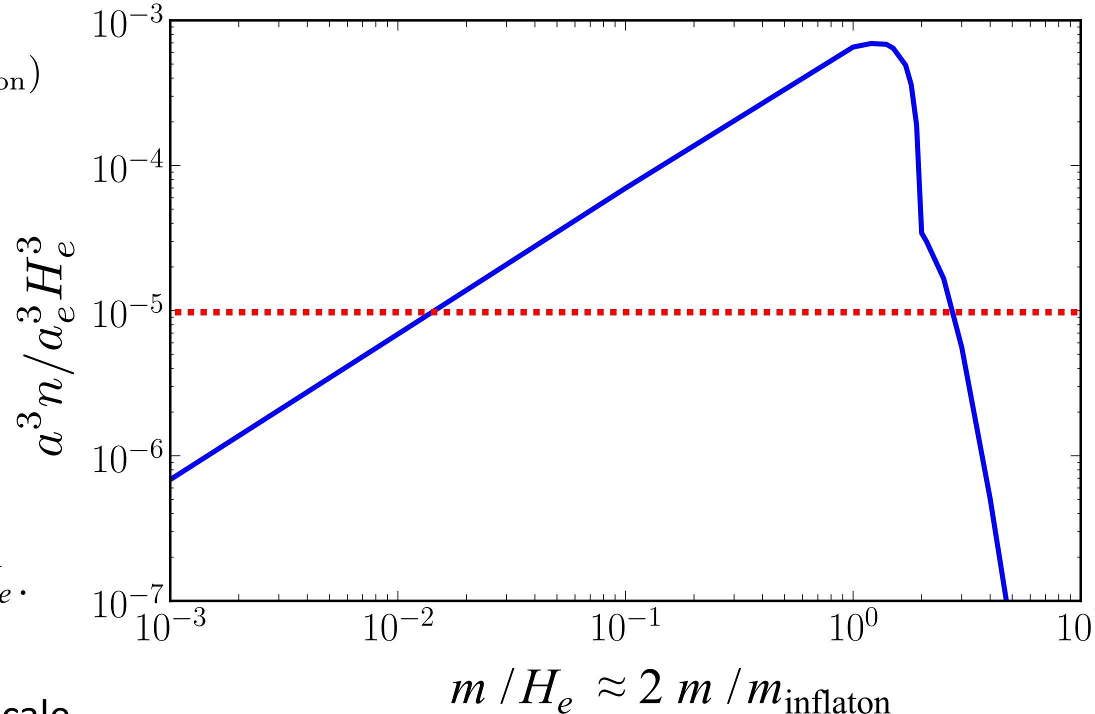
Quadratic Inflaton Potential for Conformally-Coupled Scalar: $\xi = 1/6$

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

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

- 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 $H_e \approx 10^{11}$ GeV and $T_{\mathrm{RH}} \approx 10^9$ GeV are "common."
- If stable and dark matter, $\Omega\, h^2 = 0.12 \implies m \approx H_e$.
  Could have been anything! WIMPZILLA miracle!
- Perhaps inflation scale represents new physics scale, stable particle at that mass scale natural DM candidate.

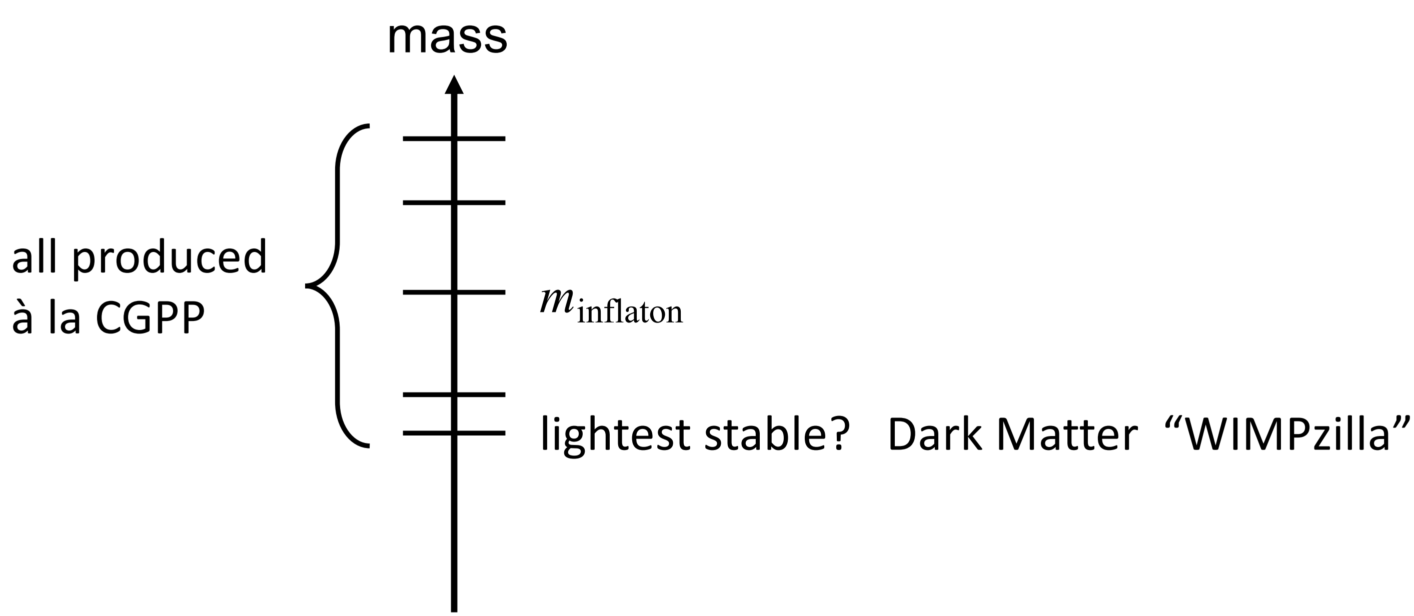
Conformally coupled scalar $\xi = 1/6$



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

GPP & Dark Matter

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



dRGT Potential

$$V(\mathbb{X};\beta_n) \equiv \sum_{n=0}^{4} \beta_n S_n(\mathbb{X})\,, \quad S_n(\mathbb{X}) \equiv \mathbb{X}^{\mu_1}_{[\mu_1} \ldots \mathbb{X}^{\mu_n}_{\mu_n]}\,, \quad \mathbb{X}^{\mu}{}_{\nu} = (\sqrt{g^{-1}f})^{\mu}{}_{\nu}$$

Five parameters: β_0 … β_4. Only three combinations enter at quadratic order

$\beta_1 + 2\beta_2 + \beta_3 = 1$ (Normalizes Fierz-Pauli mass to be m)

$$\Lambda_g = m^2\big(\beta_0 + 3\beta_1 + 3\beta_2 + \beta_3\big)$$

$$\Lambda_f = m^2\big(\beta_1 + 3\beta_2 + 3\beta_3 + \beta_4\big)$$

$\Lambda = 0$; inflation driven by ϕ_g and ϕ_f

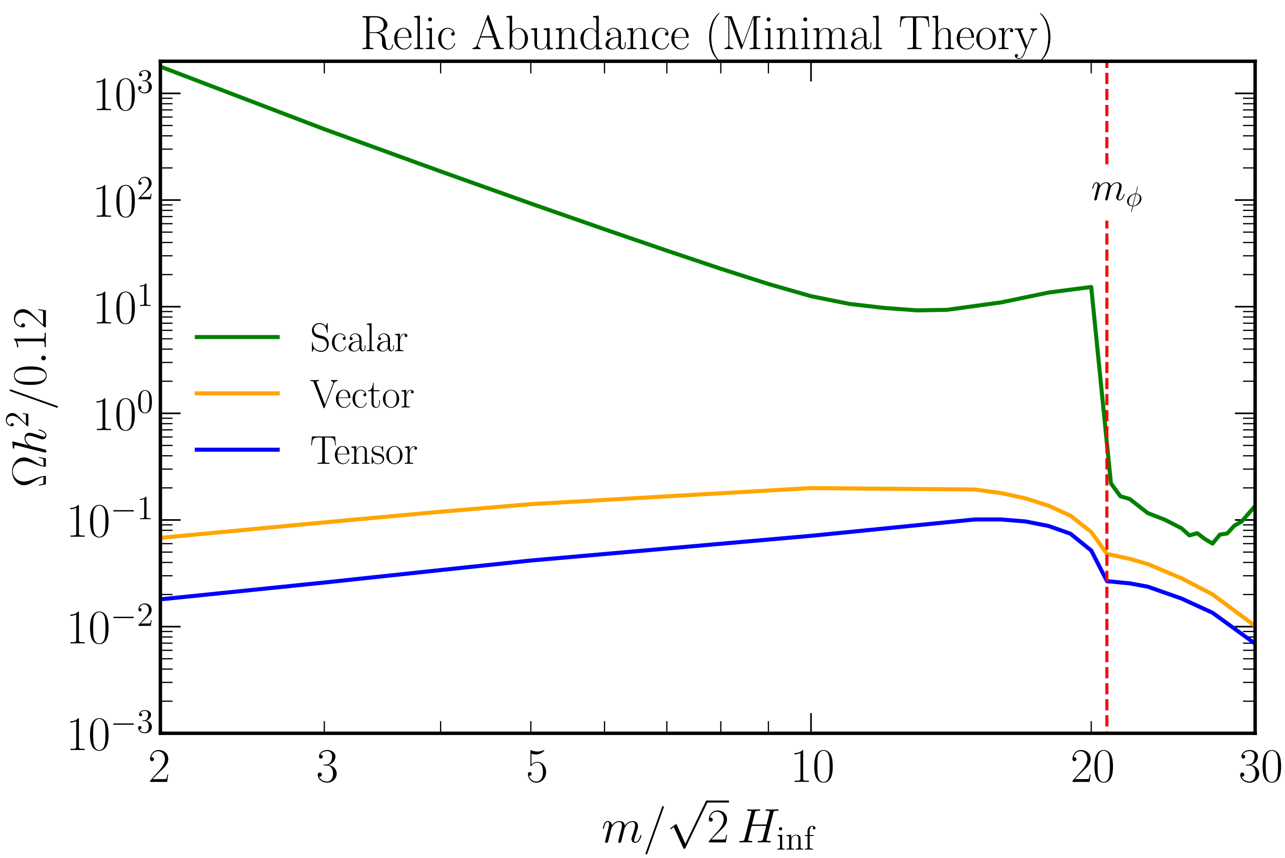
Three masses: $M_g^2,\ M_f^2,\ m^2$

$$M_*^2 = (M_g^{-2} + M_f^{-2})^{-1}$$

$$M_P^2 = M_g^2 + M_f^2$$

Relic Abundance (Assuming Stable)

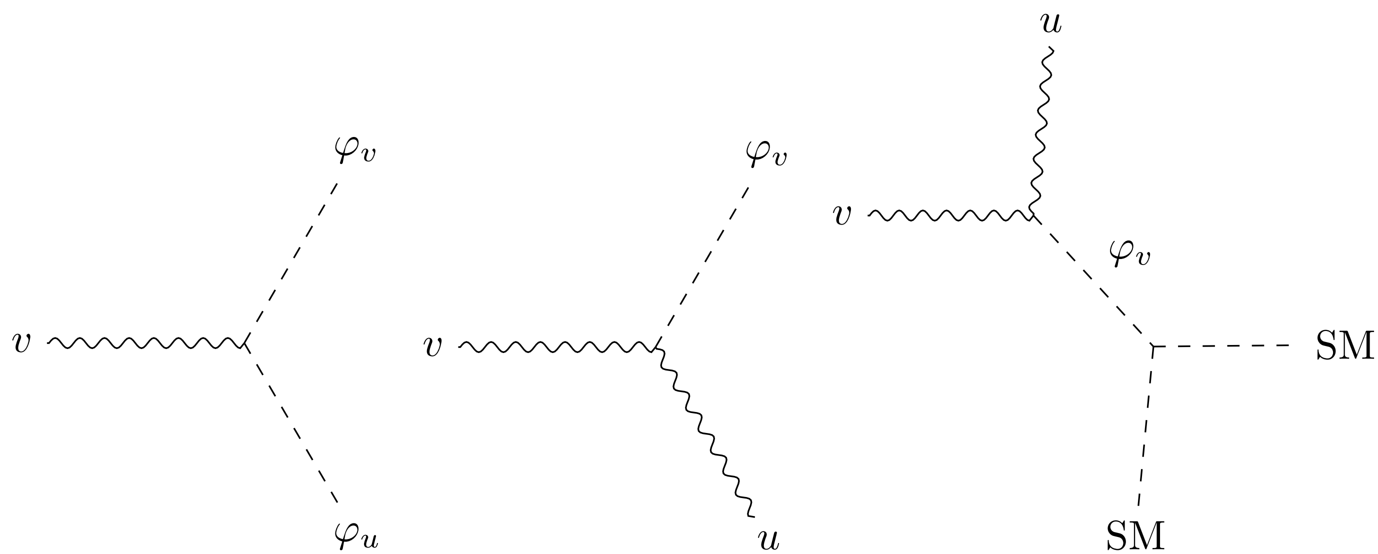
$$\frac{\Omega h^2}{0.12} \approx \frac{m}{10^{10}\mathrm{GeV}} \; \frac{H_e}{10^{10}\mathrm{GeV}} \; \frac{T_{\mathrm{RH}}}{10^{8}\mathrm{GeV}} \; \frac{a^3 n}{a_e^3 H_e^3}$$



For $T_{\mathrm{RH}} = 10^5$ GeV

Expect Massive Spin–2 Unstable

Beyond quadratic order—require bigravity formalism



$$\Gamma \sim \left(\frac{m^2}{M_P}\right)^2 \frac{1}{m} \sim \frac{m^3}{M_P^2}$$

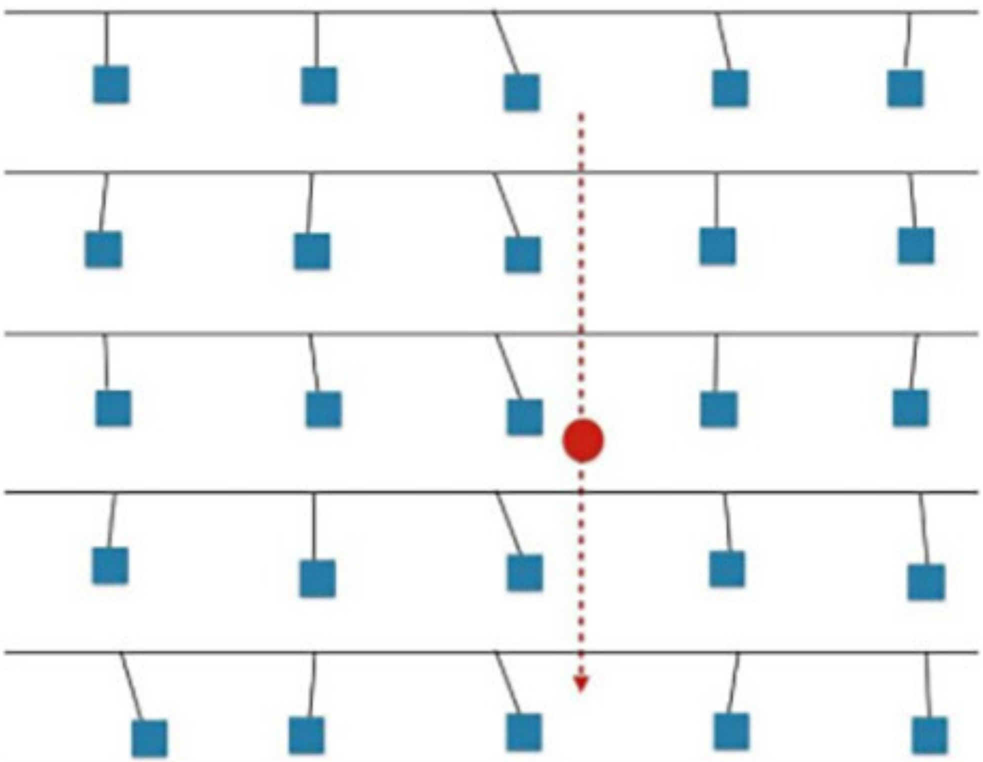
Much Recent Work … Many Open Roads

- 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-Like-Particle (KRLP)?
- Long-lived massive particles from CGPP
  - Baryo/leptogenesis?
  - ….
- Direct detection?

Windchime: Detect WIMPzillas with only gravitational coupling

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

Windchime



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

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?

Baron Ernst Carl Gerlach Stueckelberg von Breidenbach zu Breidenstein und Melsbach