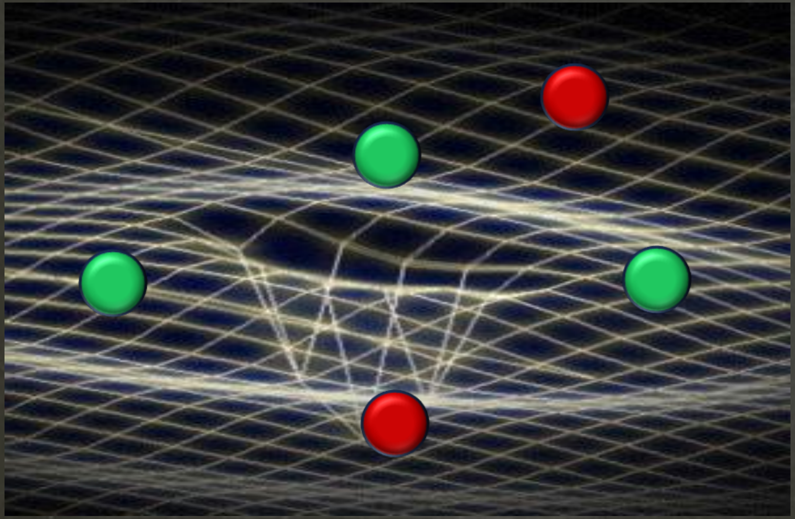
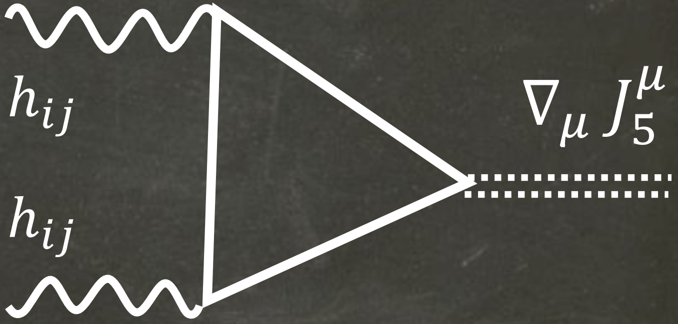
Gravitational ABJ Anomaly
Stochastic Matter Production & Leptogenesis



Azadeh Malek-Nejad

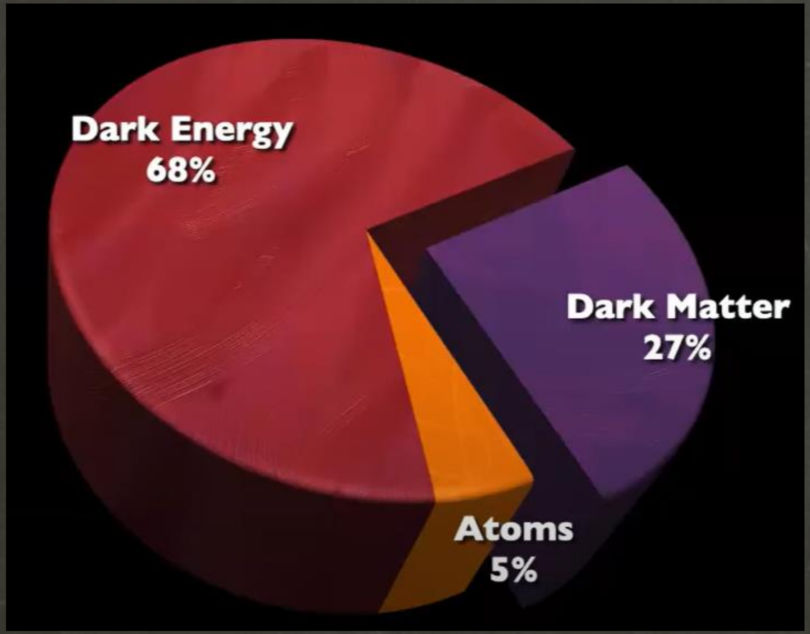
King's College London



arXiv:2412.09490

The Story Behind this Story!

32% of the Universe today is made of Matter, visible & dark



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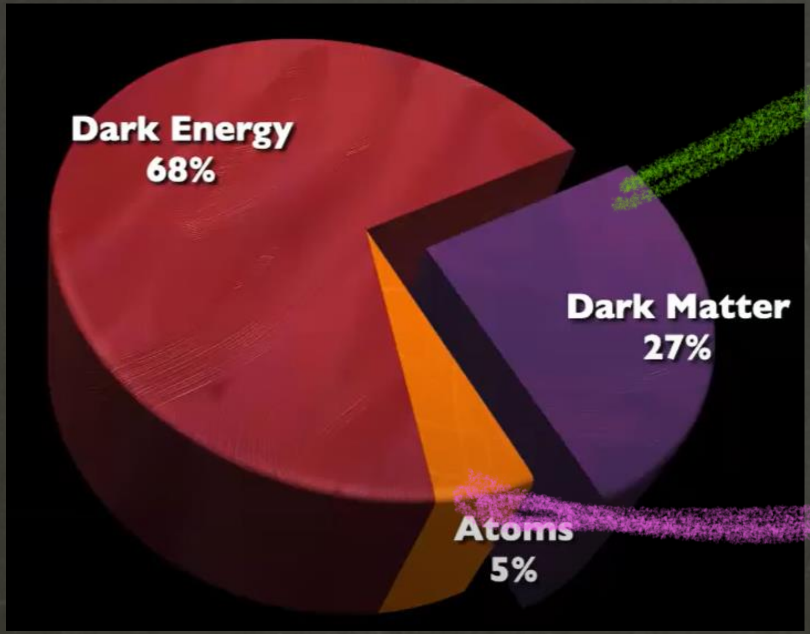
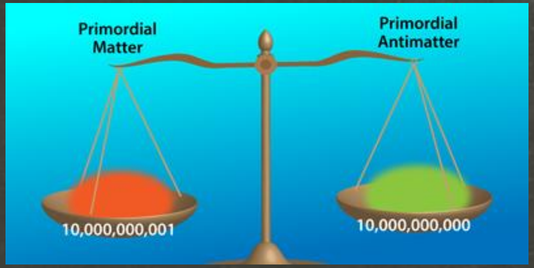


i) Particle Nature of DM
ii) Its Production mechanism

Requires CP violation beyond the SM

Matter – antimatter Asymmetry!



Common Puzzles of SM & Cosmology

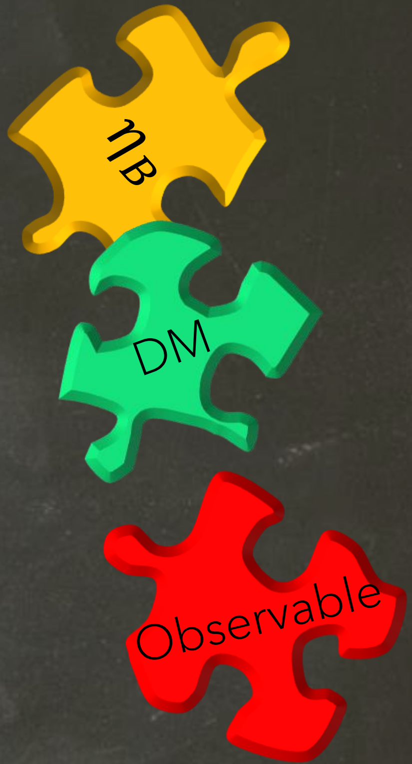
I) Origin of matter asymmetry

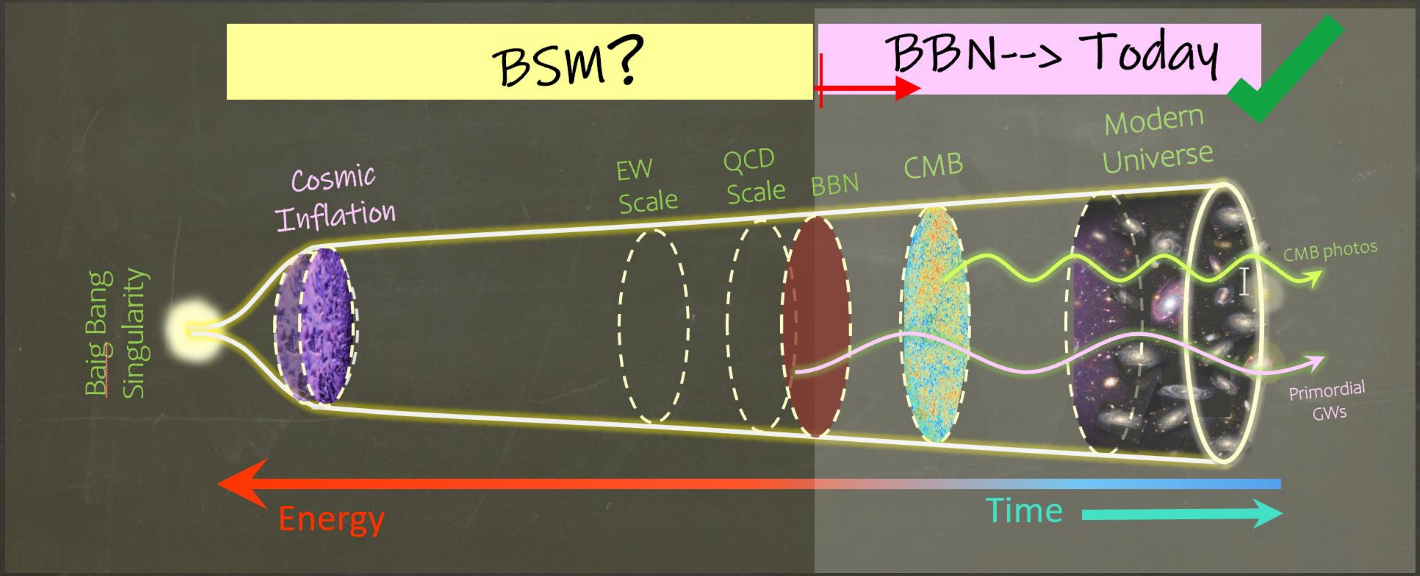
II) Particle nature of DM

III) How DM has been produced?

Puzzles which need **Physics Beyond SM**

We often assume New Physics Interactions
To Answer this Question!





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Puzzles which need **Physics Beyond SM**

We often assume New Physics Interactions
To Answer this Question!
But
What about Gravitational Fields?

Setup

1) Quantum Fluctuations in Cosmology

2) Gravitational Particle Production

3) Gravitational ABJ Anomaly

arXiv:2412.09490

4) Outlook

Quantum Fluctuations in Cosmology

$$\hbar \neq 0$$

Quantum Vacuum $\hbar \neq 0$

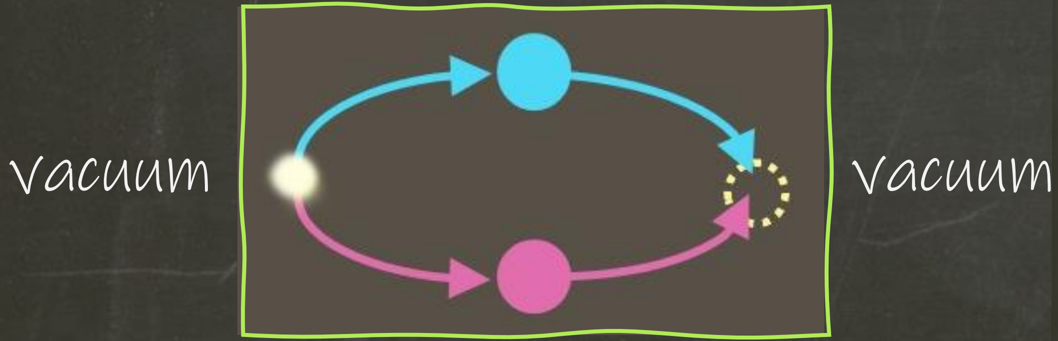
Due to Uncertainty Principle

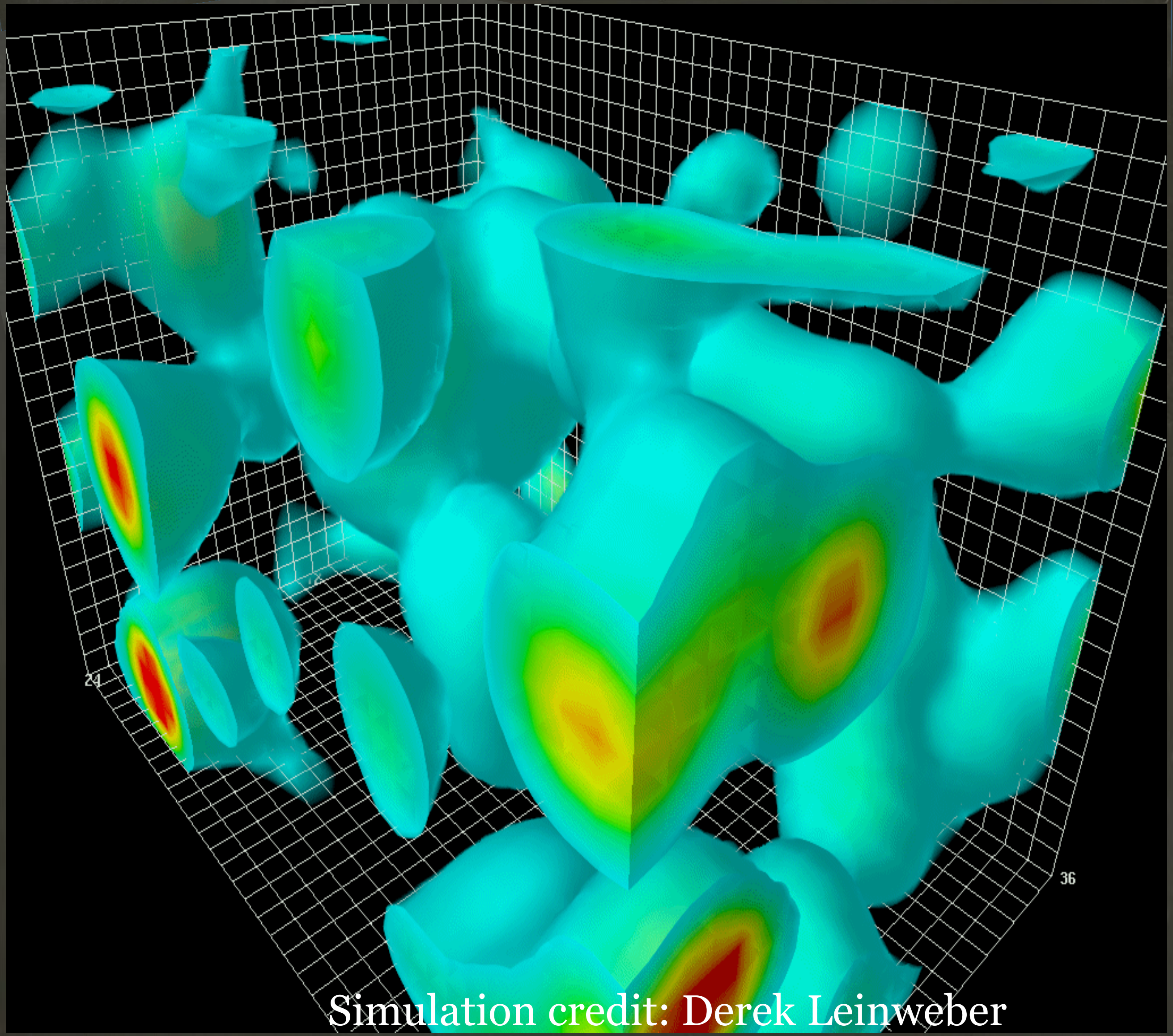
$$\Delta x\, \Delta p \geq \hbar/_2$$

quantum vacuum is NOT nothing!

But, a vast ocean made of

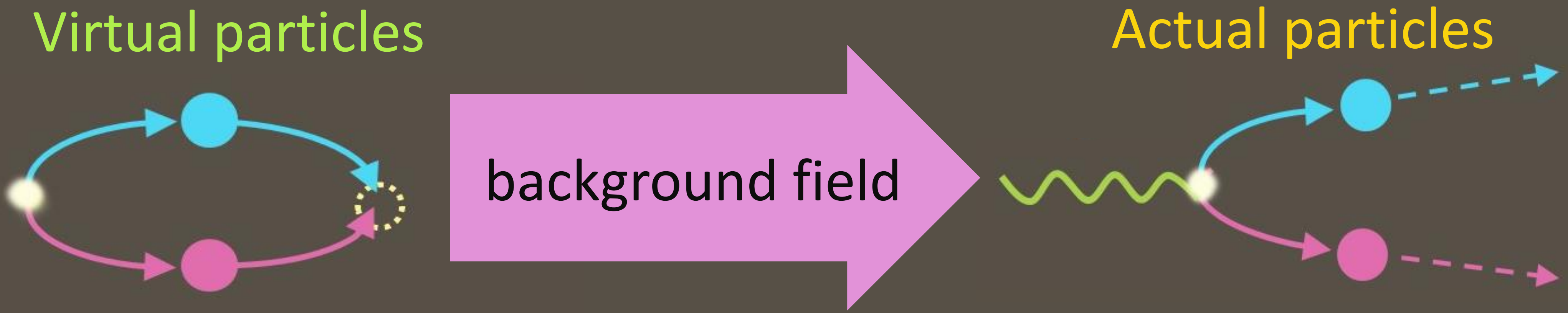
Virtual particles





Quantum Vacuum

Particle Production



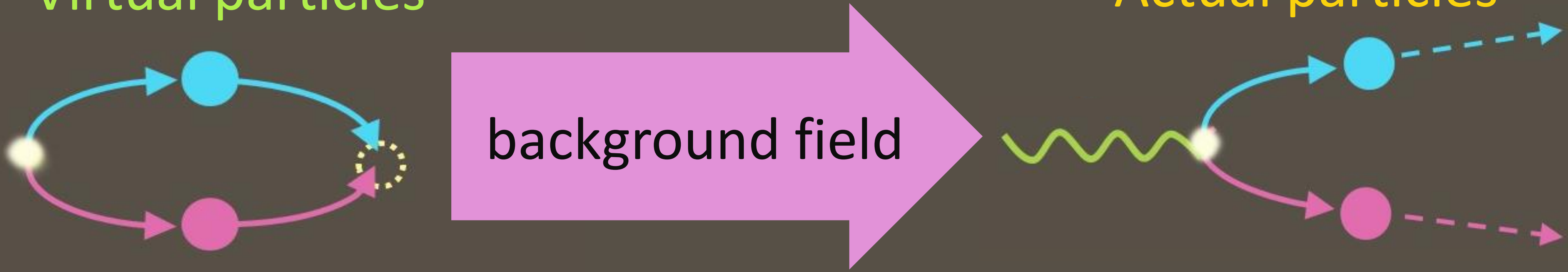
Background field can upgrade them into actual particles!

$\langle J \rangle = 0$

$\langle J \rangle \neq 0$

Quantum Vacuum → Particle Production

Virtual particles | Actual particles



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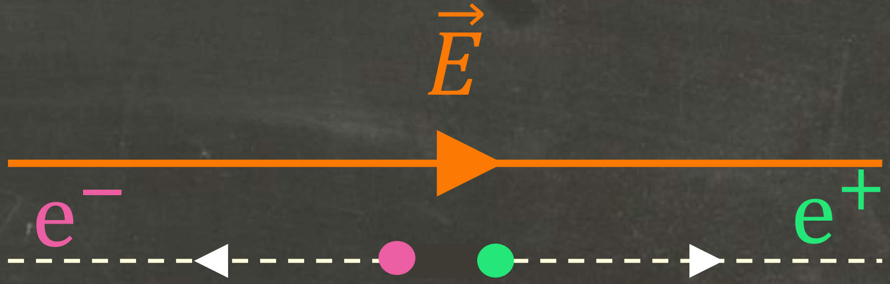
Examples of such BG fields:

1) Electric Field *Schwinger effect*



Work of the Lorentz force over Comptom wavelength

$$eE\,\lambda_{comp} = mc^2$$

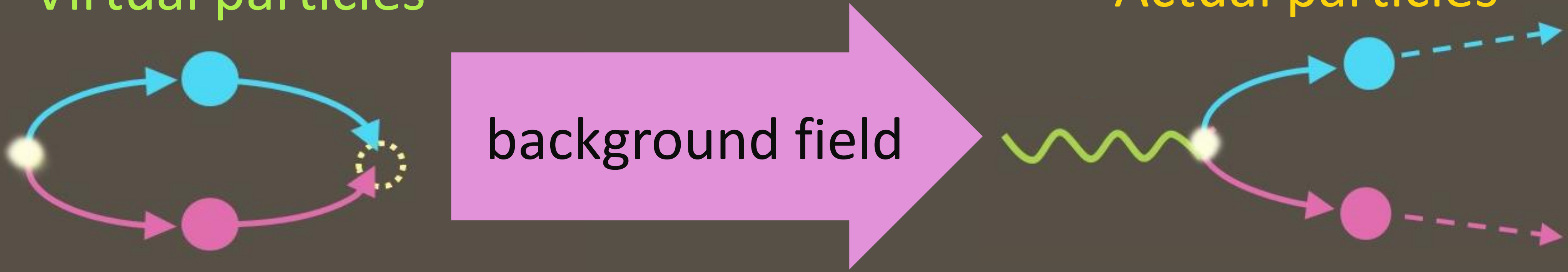
Rest energy of charged particle

J. Schwinger (1951)

Quantum Vacuum → Particle Production

Virtual particles

Actual particles



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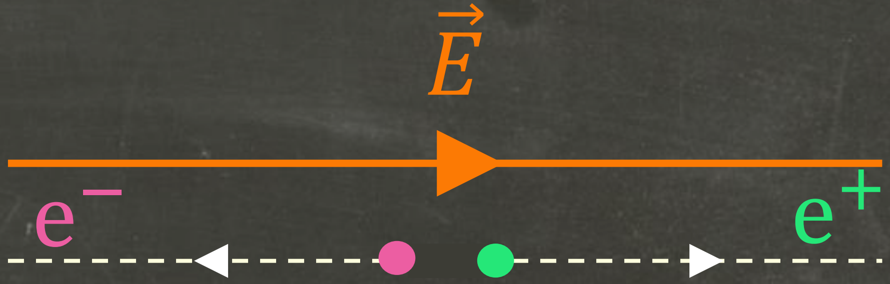
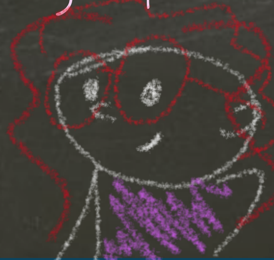


Work of the Lorentz force over Comptom wavelength

$$eE\,\lambda_{comp} = mc^2$$

Rest energy of charged particle

The Electric field that can create electron pairs $E = \frac{m_e^2 c^3}{e\hbar} = 10^{18}\ V/m$



J. Schwinger (1951)

What about

Schwinger Effect in Early Universe?

How about **Axion-inflation?!**

i) a natural candidate for the inflaton field

ii) Naturally coupled to gauge fields

Schwinger effect in axion-inflation

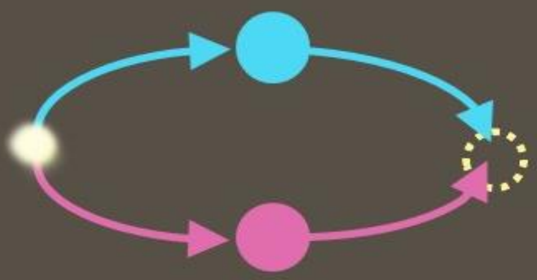
K. Lozanov

E. Komatsu

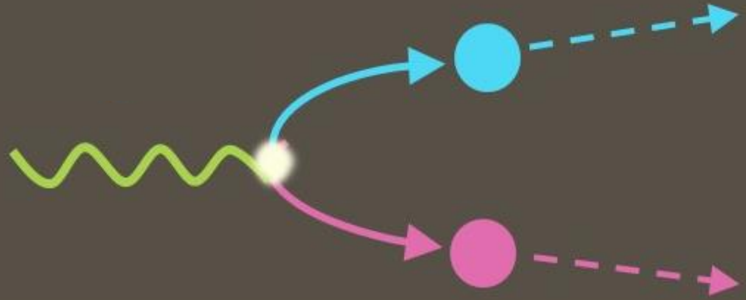
- K. Lozanov, **A. M.**, E. Komatsu **2018**
- **A. M.**, E. Komatsu **2019**
- V. Domcke, Y. Ema, K. Mukaida, R. Sato 2019
- L. Mirzagholi, **A. M.**, K. Lozanov **2019**
- ....
- E. Komatsu **2022** **nature reviews** physics
  New physics from the polarized light of the cosmic microwave background

Quantum Vacuum — Particle Production

Virtual particles → **Actual particles**



background field

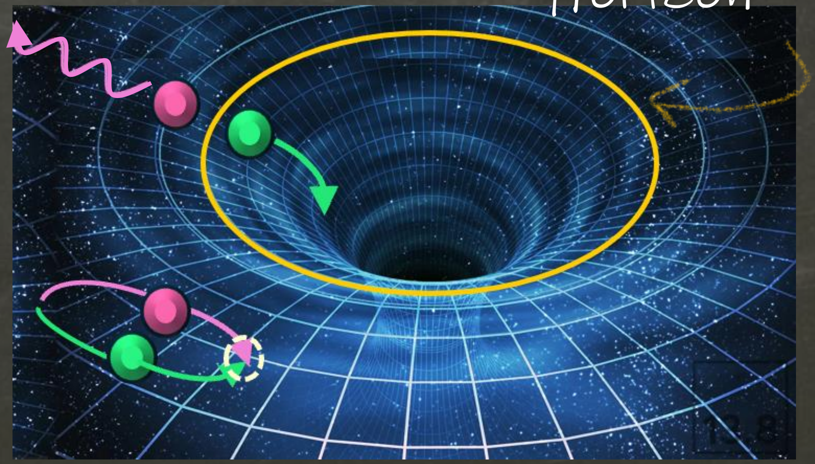


Background field can upgrade them into actual particles!

Examples of such BG fields:

2) Gravitational

Hawking radiation



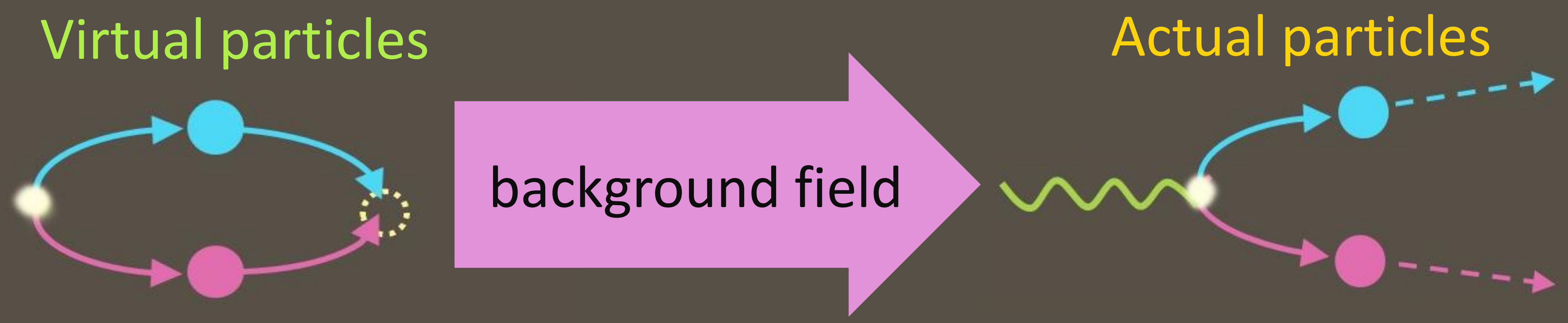
one particle fall into the BH, while the other escapes…

S. Hawking (1974)

Power BH emitted is

$$P = \frac{\pi c^3 M_{pl}^4}{240} \frac{1}{M^2}$$

Quantum Vacuum   Particle Production



Background field can upgrade them into actual particles!

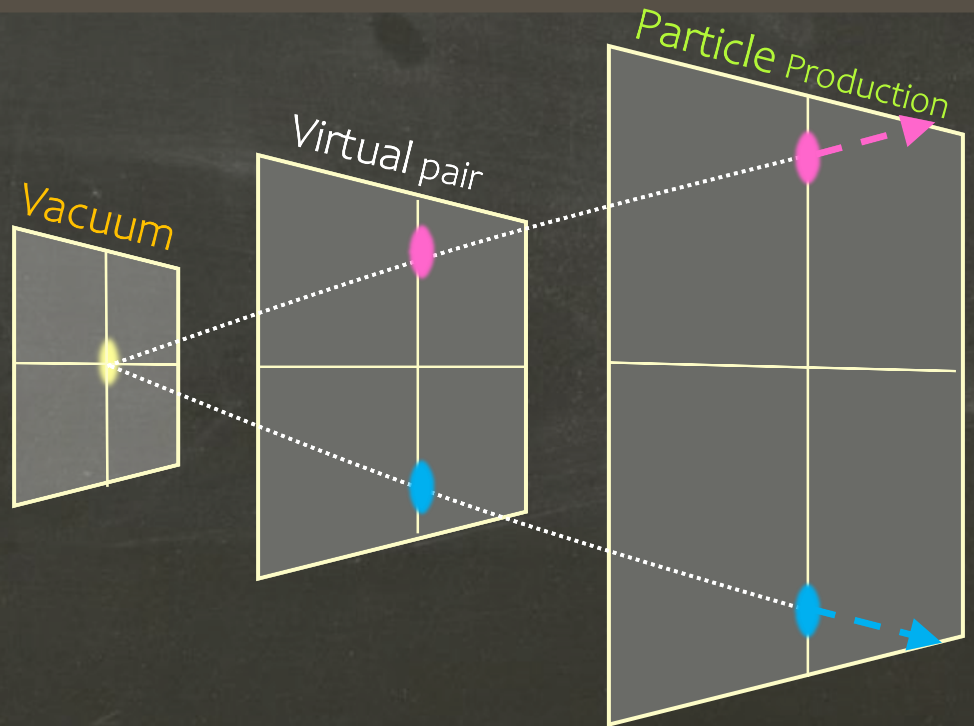
Examples of such BG fields:

1) Electric Field   *Schwinger effect*

2) Gravitational

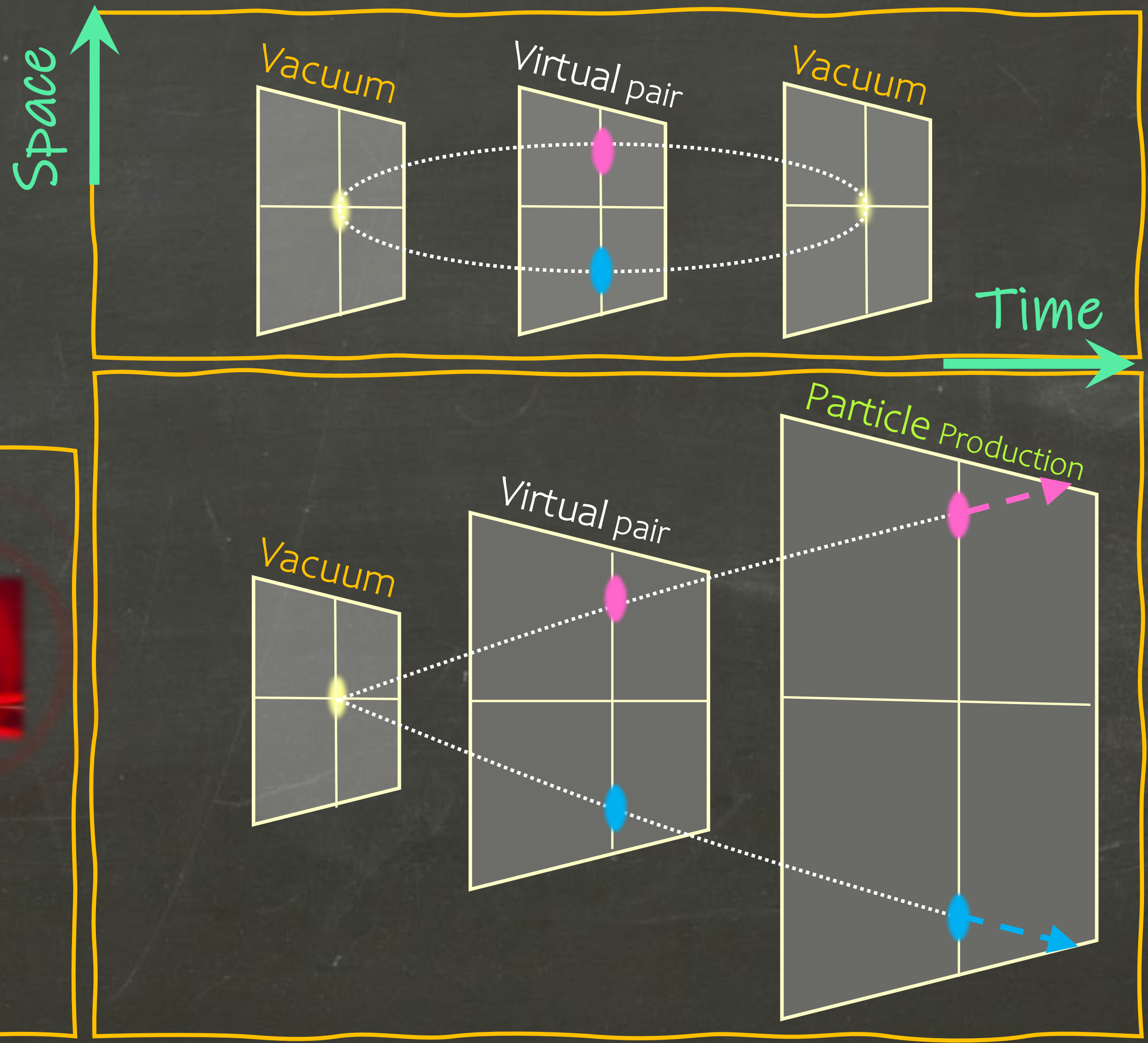
i) Hawking radiation

ii) expansion of the Universe!



Expanding Universe Produces Particles!

Flat Space:



Vacuum

Expanding space:

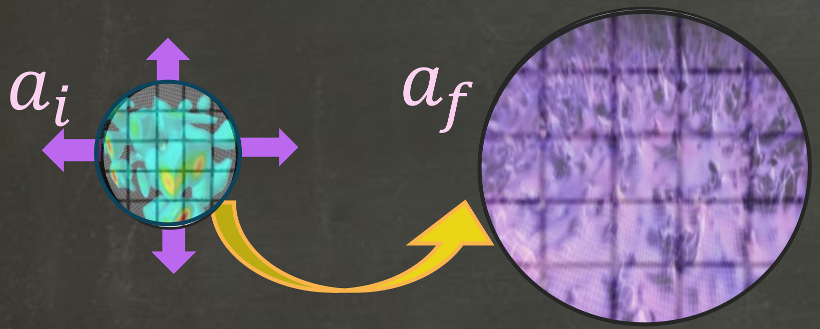
Particle Production

E. Schrödinger (1939)

Shocked by his discovery, Schrödinger found it an alarming phenomenon!

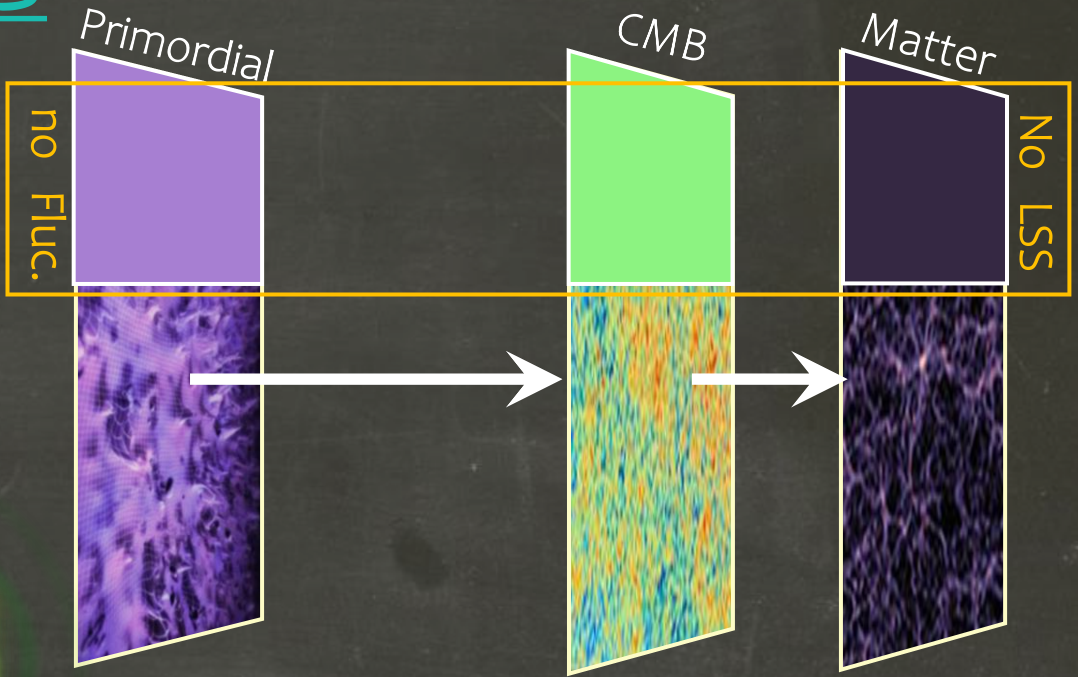
Cosmic Perturbations

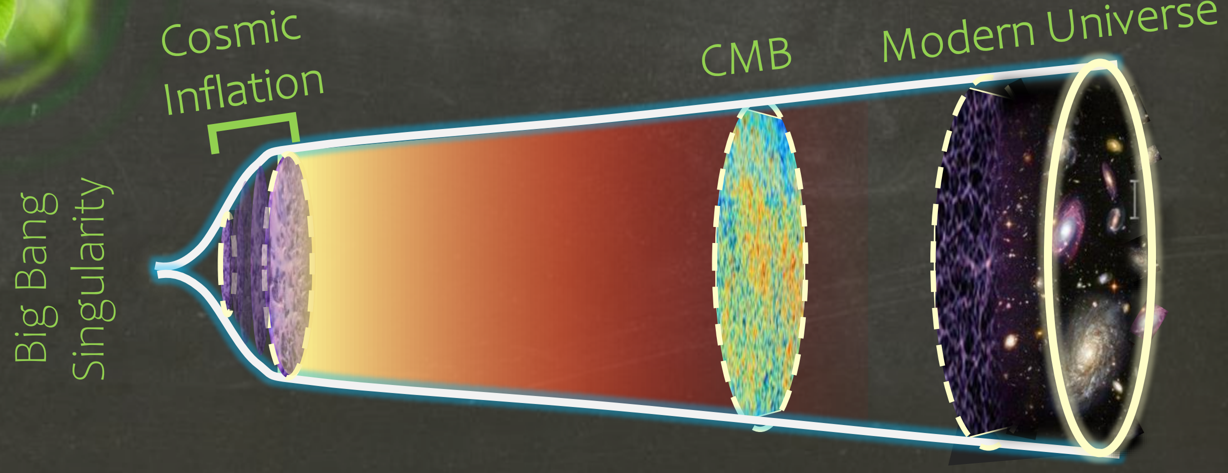
Exponential expansion turns initial quantum vacuum fluctuations into



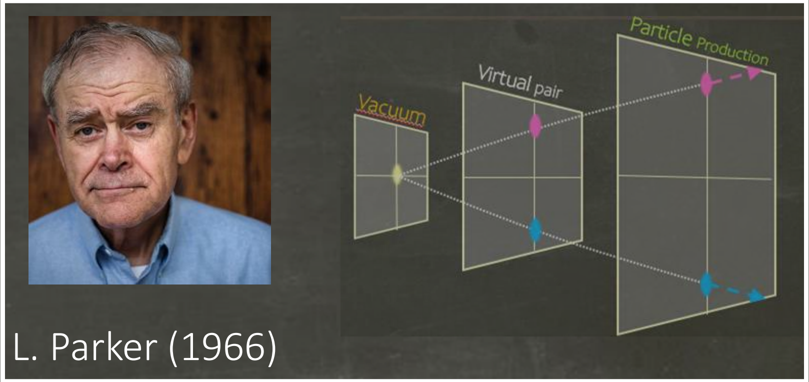
actual cosmic perturbations!

We are the product of quantum fluctuations in the very early universe!





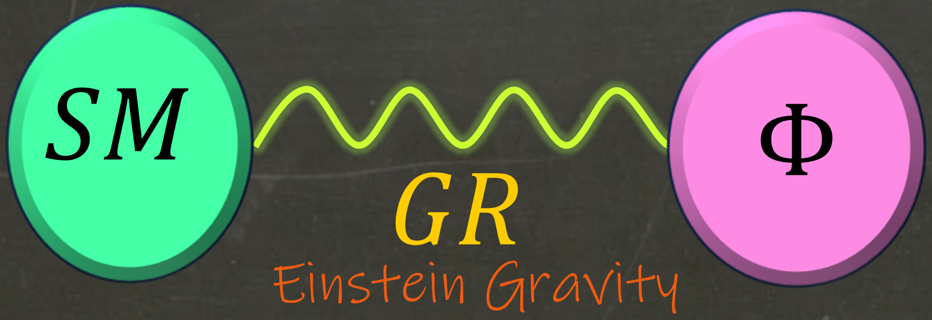
Cosmological Gravitational Particle Production (CGPP)



L. Parker (1966)

The expansion of the Universe creates pair production in FRW geometry.

But conformal fields in 4d will not be produced since FRW is conformally flat!



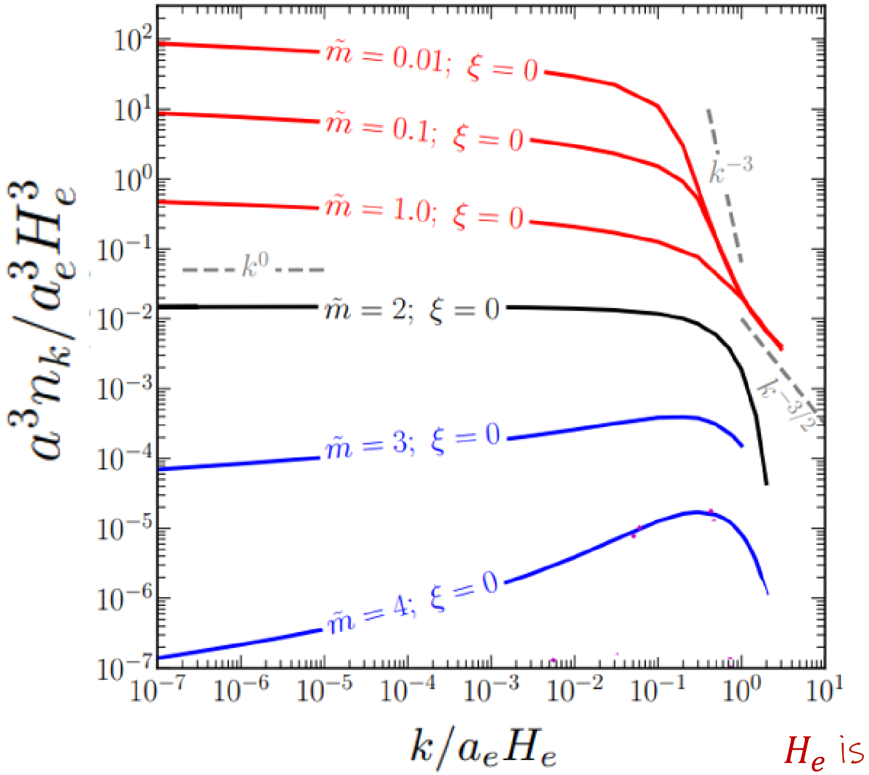
Scalar Field in Expanding Universe

Consider a scalar field $\mathcal{L} = \frac{1}{2} g^{\mu\nu} \nabla_\mu \Phi \nabla_\nu \Phi - \frac{1}{2} m^2 \Phi^2$

In cosmological background $g_{\mu\nu} = a^2(\tau)\mathrm{diag}(-1, 1, 1, 1)$

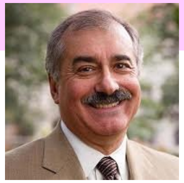
$$\Phi_k'' + \omega_k^2(\tau)\Phi_k = 0$$

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



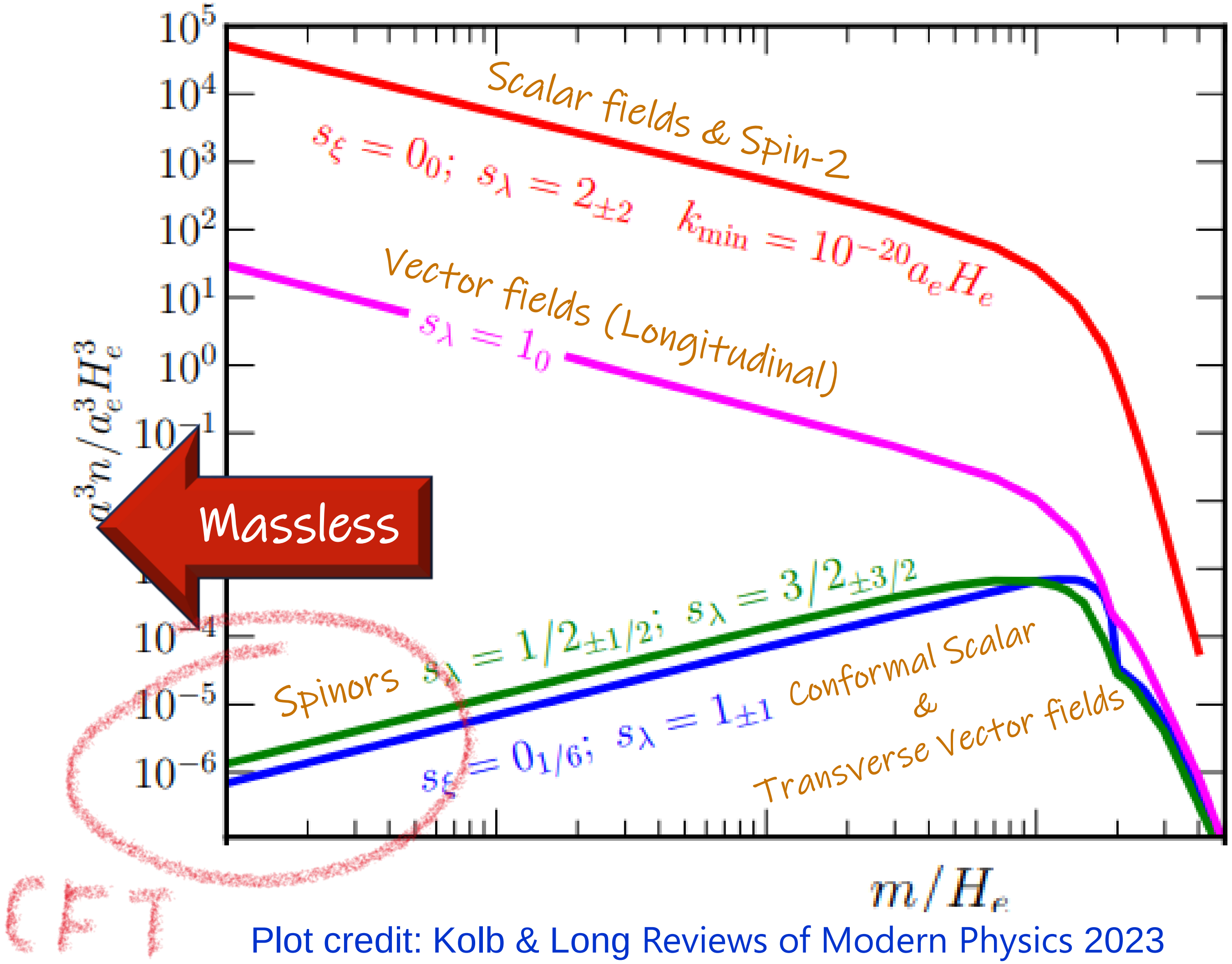
An example of **Cosmological Gravitational Particle Production (CGPP)**

Plot credit: Kolb & Long Reviews of Modern Physics 2023




H_e is Hubble scale at the end of inflation

Spinning Fields in Expanding Universe



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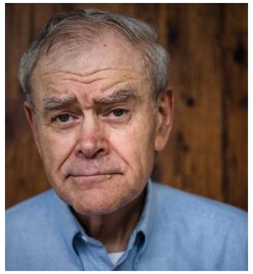

L. Parker (1966)

Conformal fields in FRW will not be produced since FRW is conformally flat!

No CGPP for massless fermions!

(conformal symmetry)

Fermions in Expanding Universe

Consider spin $\frac{1}{2}$ massless fermions $\mathcal{L}_\psi = i\psi^\dagger\,\gamma^\mu \mathcal{D}_\mu \psi$

Spinor covariant derivative $\mathcal{D}_\mu = \nabla_\mu - \omega_\mu$ Spin connection

In cosmological background $g_{\mu\nu} = a^2(\tau)\mathrm{diag}(-1,1,1,1)$

The field equation of fermion is $\left(\gamma^0(\partial_0 + \frac{3}{2}H) + \frac{1}{a}\gamma^i\partial_i\right)\psi = 0.$

Effect of gravity

The effect of FRW gravity (conformally flat geometry) can be absorbed as

$$\Psi \equiv a^{3/2}\psi, \longrightarrow \left(\gamma^0\,\partial_0 + \frac{1}{a}\gamma^i\partial_i\right)\Psi = 0.$$

canonically renormalized field lives in flat space!

How to Create Fermions in Expanding Universe?

Breaking the conformal symmetry of Weyl fermions by interactions, e.g.

(dilatation transformation)

- Couple your Weyl fermion with { Inflaton field, Standard Model, Dark sector coupled to thermal bath

- make the fermion massive to produce them gravitationally! (CGPP)

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Is that the best Gravity can do to produce fermions!?

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Gravitational Particle Production Mechanisms

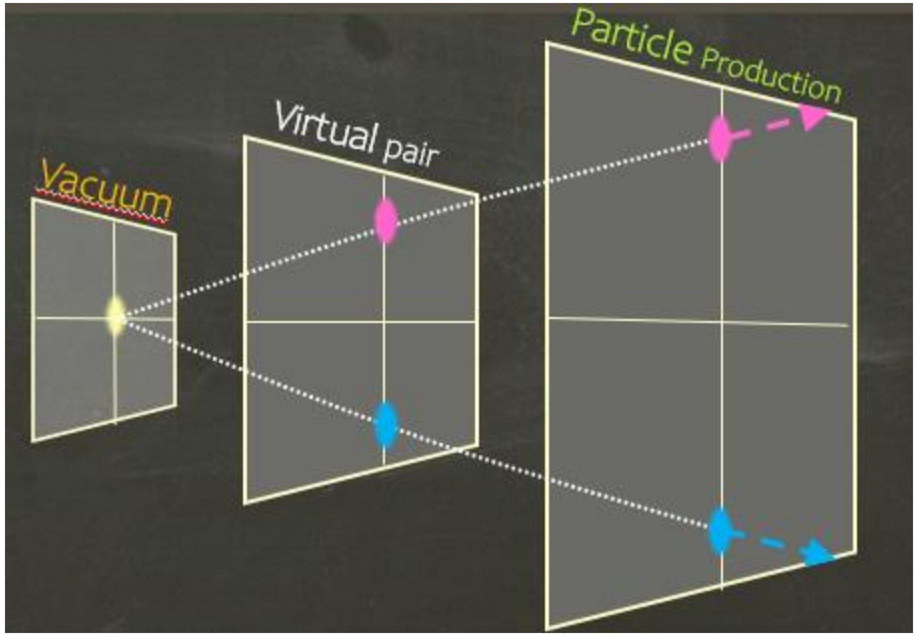
Gravitational Particle Production Mechanisms

Production Mechanism	Underlying Physics	Conditions
I) Cosmological Gravitational Particle Production (CGPP)	Cosmic expansion	super-massive fields $M > 10^{13}\ GeV$

Kolb & Long 2017

Relic density by CGPP

$$\frac{\rho_{\Psi,0}^{\rm CGPP}}{\rho_{\rm DM,0}} \sim 7 \times \left(\frac{M}{10^{11}{\rm GeV}}\right)^2 \left(\frac{T_{\rm reh}}{10^9{\rm GeV}}\right),$$



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	Production Mechanism	Underlying Physics	Conditions	
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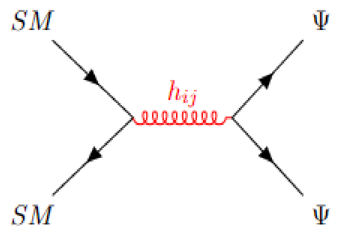
II)	Graviton-Mediated Annihilation (GMA)		Super-massive field High temperature plasma $T_{reh} > 10^{13}$ GeV	M. Garny, et al 2016 Bernal, et. al. 2018 Clery et. al. 2022

Relic density by GMA

$$\frac{\rho_{\Psi,0}^{\rm GMA}}{\rho_{\rm DM,0}} \sim 5\left(\frac{M}{10^{12}{\rm GeV}}\right)\left(\frac{T_{\rm reh}}{10^{13}{\rm GeV}}\right)^3,$$

Gravitational Particle Production Mechanisms

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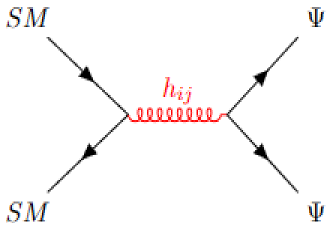
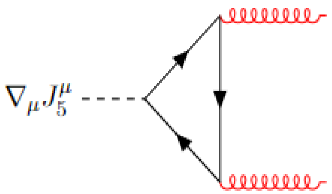
II)	Graviton-Mediated Annihilation (GMA)		Super-massive field High temperature plasma $T_{reh} > 10^{13}\ GeV$	M. Garny, et al 2016 Bernal, et. al. 2018 Clery et. al. 2022
III)	Gravitational Leptogenesis		Parity violation $h_L \neq h_R$ Chiral GWs Chiral fermions	Alexander et. al. 2006 **A.M.** 2014 & 2016 **A.M.** 2024

Chiral fermions

(global) Gravitational anomaly

$$\nabla_\mu J_5^\mu = \frac{N_L - N_R}{16\pi^2} R\tilde{R}$$

Gravitational Particle Production Mechanisms

	Production Mechanism	Underlying Physics	Conditions	
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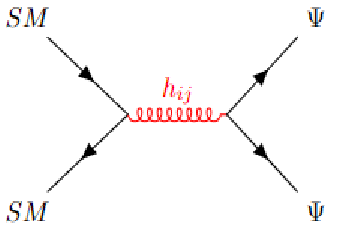
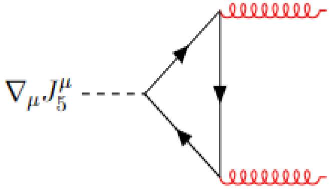
II)	Graviton-Mediated Annihilation (GMA)		Super-massive field High temperature plasma $T_{reh} > 10^{13}\ GeV$	M. Garny, et al 2016 Bernal, et. al. 2018 Clery et. al. 2022
III)	Gravitational Leptogenesis		Parity violation Chiral GWs Chiral fermions	Alexander et. al. 2006 **A.M.** 2014 & 2016 **A.M.** 2024

$h_L \neq h_R$

What does Unpolarized Gravitational Waves do!?

Gravitational Particle Production Mechanisms

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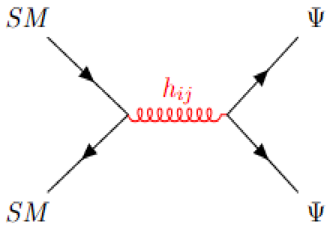
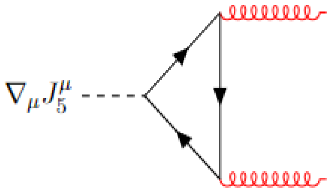
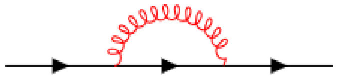
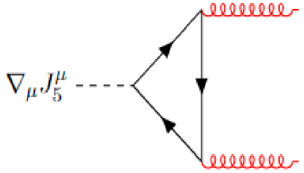
I)	Cosmological Gravitational Particle Production (CGPP)	Cosmic expansion	super-massive fields M> 10^{13} GeV	Kolb & Long 2017
II)	Graviton-Mediated Annihilation (GMA)		Super-massive field High temperature plasma $T_{reh} > 10^{13}$ GeV	M. Garny, et al 2016 Bernal, et. al. 2018 Clery et. al. 2022
III)	Gravitational Leptogenesis		Parity violation $h_L \neq h_R$ Chiral GWs Chiral fermions	Alexander et. al. 2006 **A.M.** 2014 & 2016
IV)	GW-Induced Freeze-In		GWs Background	**A.M.** & Kopp 2024

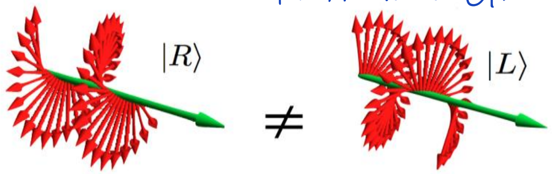
Joachim Kopp

Matter Asymmetry by Gravitational Anomaly: $\langle R\tilde{R}\rangle \neq 0!$



What makes Chiral Gravitational Waves?

To generate circularly polarized GWs, we need Parity violation in inflation.
Two possible models are



1) Chern-Simons Gravity $\mathcal{L}_{eff} = \frac{1}{\Lambda}\varphi R\tilde{R}$

Alexander, Peskin, Sheikh-Jabbari 2006

2) Non-Abelian Gauge fields in axion-inflation $\mathcal{L}_{eff} = \frac{1}{\Lambda}\varphi F\tilde{F}$ (Chiral Gauge Field → Chiral GWs)

A.M., Noorbala, Sheikh-Jabbari 2012
A.M. 2014 & 2016
Caldwell, Devulder 2017
Adshead, Long, Sfakianakis 2017
Alexander, McDonough, Spergel 2018
Kamada, Kume, Yamada, Yokoyama 2019

Axion-inflation is a generic setting for leptogenesis
(All the Sakharov conditions are satisfied)
A.M. 2014

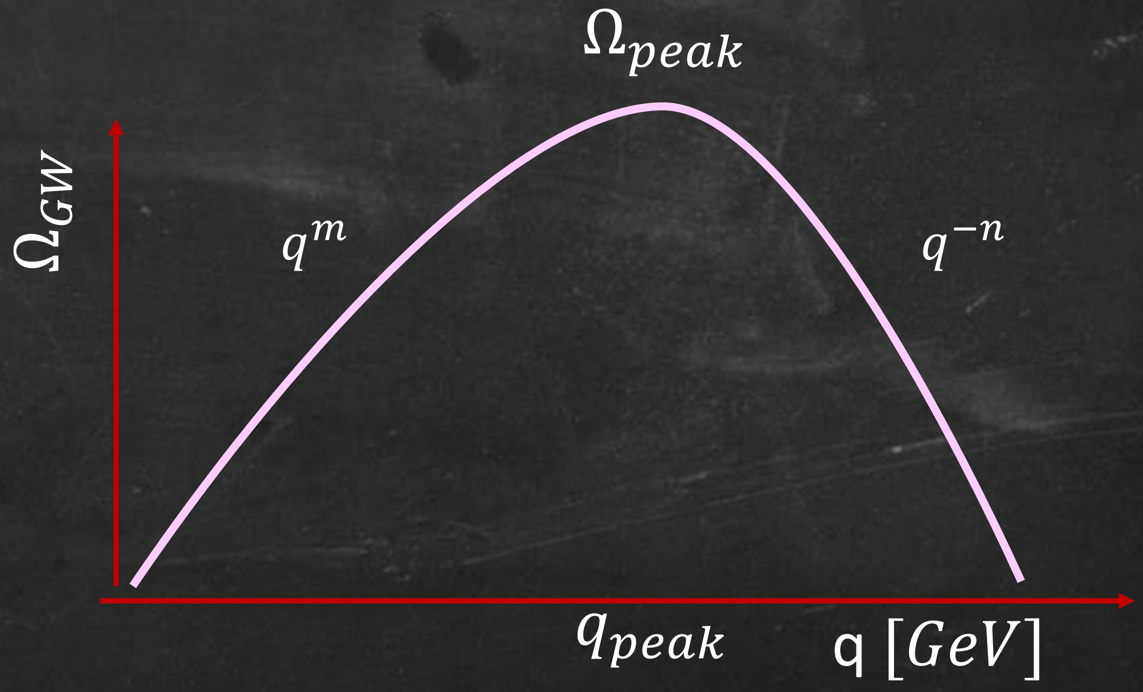
~~3) U(1) Gauge fields in axion-inflation~~

Papageorgiou, Peloso 2017

Phenomenological Model for Ω_{GW}

In radiation era

Broken Power-law Spectrum



Phenomenological Model for Ω_{GW}

$$\Omega_{\rm gw,0}(q) \approx \begin{cases} \Omega_{\rm p}\left(\frac{q}{q_{\rm p}}\right)^{m} & q_{\rm min} < q < q_{\rm p}, \\ \Omega_{\rm p}\left(\frac{q}{q_{\rm p}}\right)^{-n} & q_{\rm p} < q < q_{\rm max}, \end{cases}$$

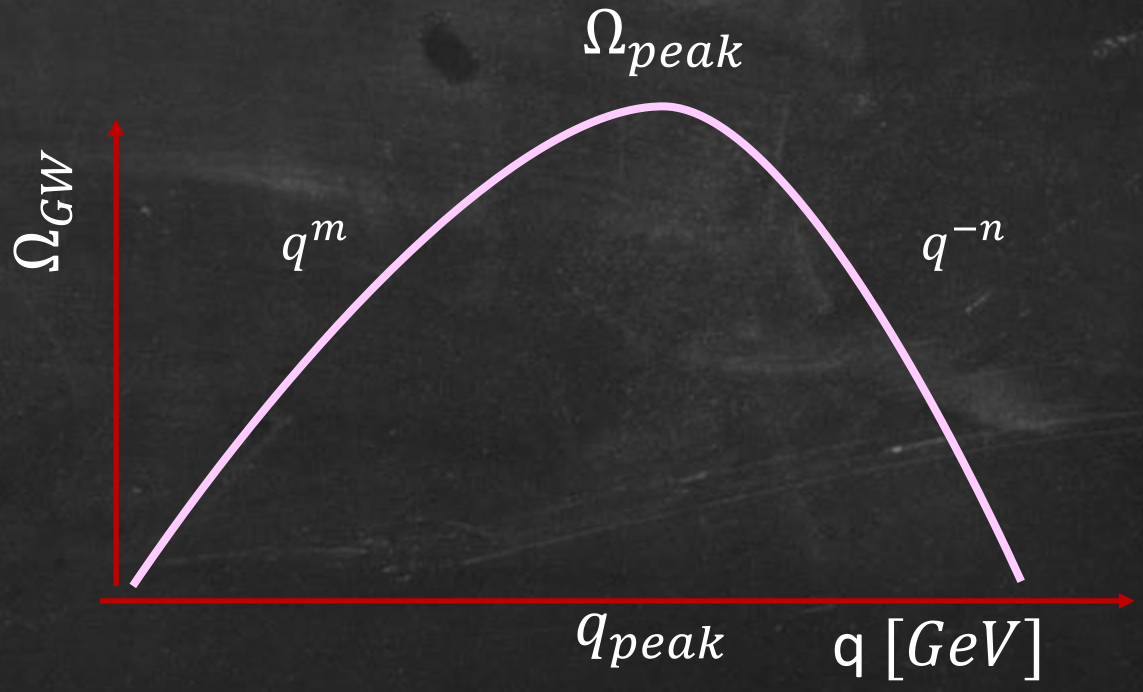
$$\Omega^{\pm}_{\rm gw,0}(q) = \frac{1 \pm \chi(q)}{2}\Omega_{\rm gw,0}(q),$$

$$\mathrm{h}_{s,\mathbf{q}}(\tau) = a^{-1}(\tau)\,\mathcal{T}_s(\tau,q)\,e^{-iq\tau}\,\mathrm{h}_{s,\mathbf{q},0},$$

$$\mathcal{T}_s(\tau,q) \approx \left(1 - e^{-\pi\beta_s(\tau-\tau_{\rm in})}\right)$$

$$\beta_{\pm} = \beta(1 \pm b_{\chi}),$$

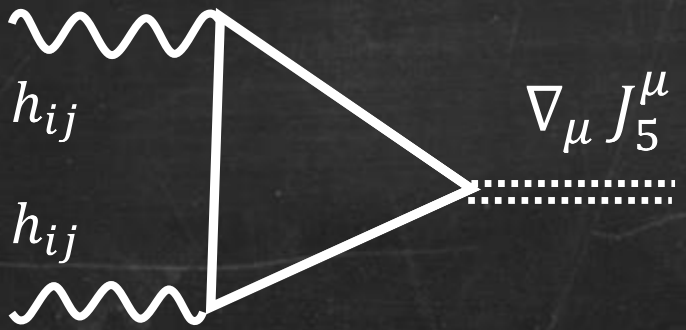
Broken Power-law Spectrum



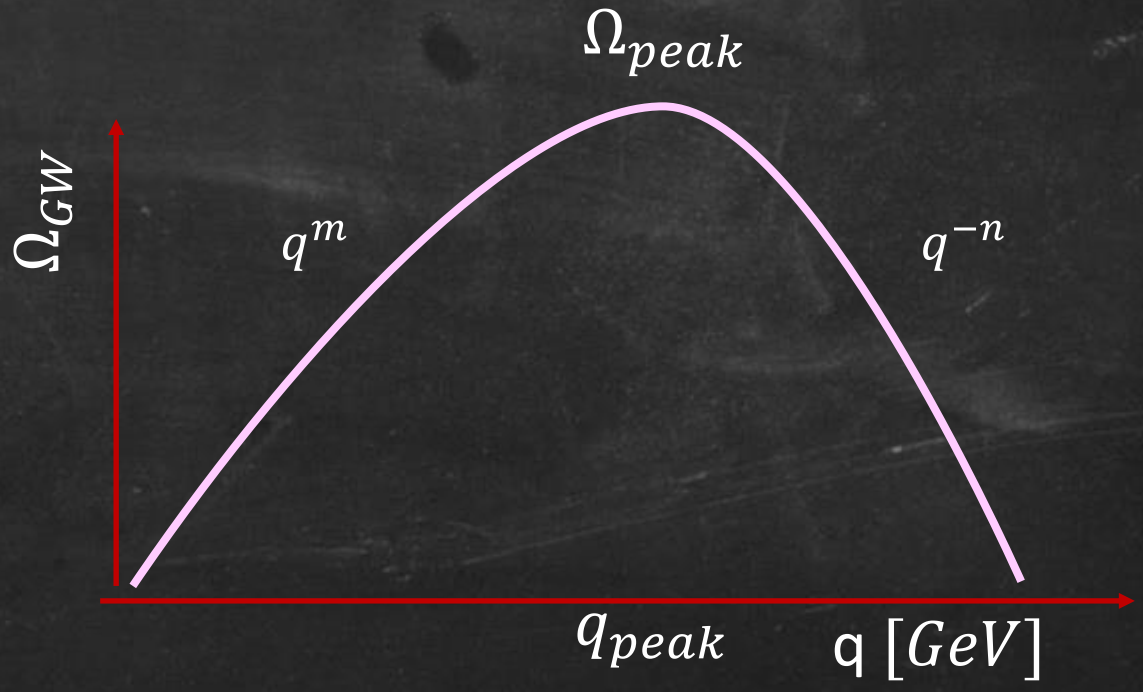
Phenomenological Model for Ω_{GW}

Gravitational ABJ Anomaly

$$\nabla_\mu J^\mu_A = \frac{N_\chi}{24(4\pi)^2}\langle R\tilde{R}\rangle,$$

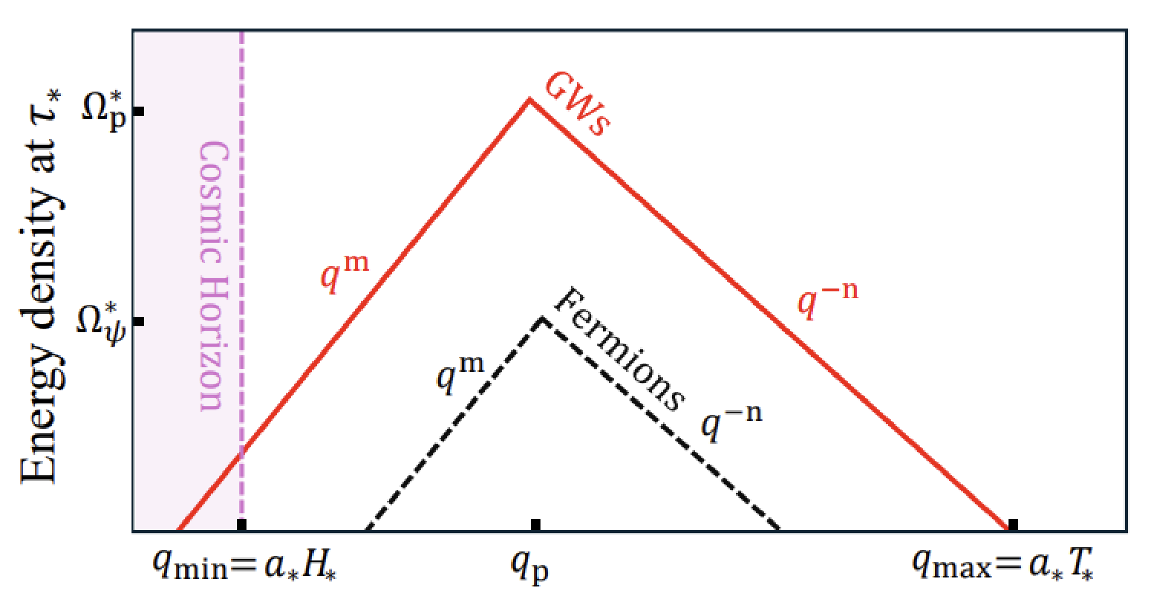


Broken Power-law Spectrum



Fermion Energy Density

$$\nabla_\mu J^\mu_A = \frac{N_\chi}{24(4\pi)^2}\langle R\tilde{R}\rangle,$$



GWs spectral energy density

$$\Omega_{\rm gw,0}(q) \approx \begin{cases} \Omega_{\rm p}\left(\frac{q}{q_{\rm p}}\right)^m & q_{\rm min} < q < q_{\rm p}, \\ \Omega_{\rm p}\left(\frac{q}{q_{\rm p}}\right)^{-n} & q_{\rm p} < q < q_{\rm max}, \end{cases}$$

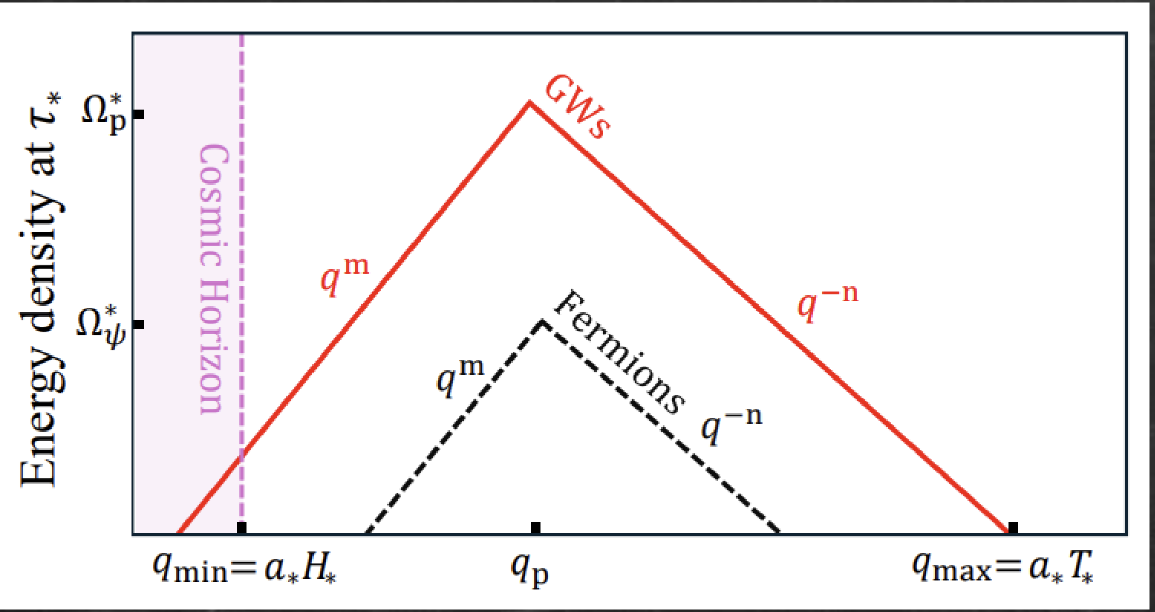
Fermions number density

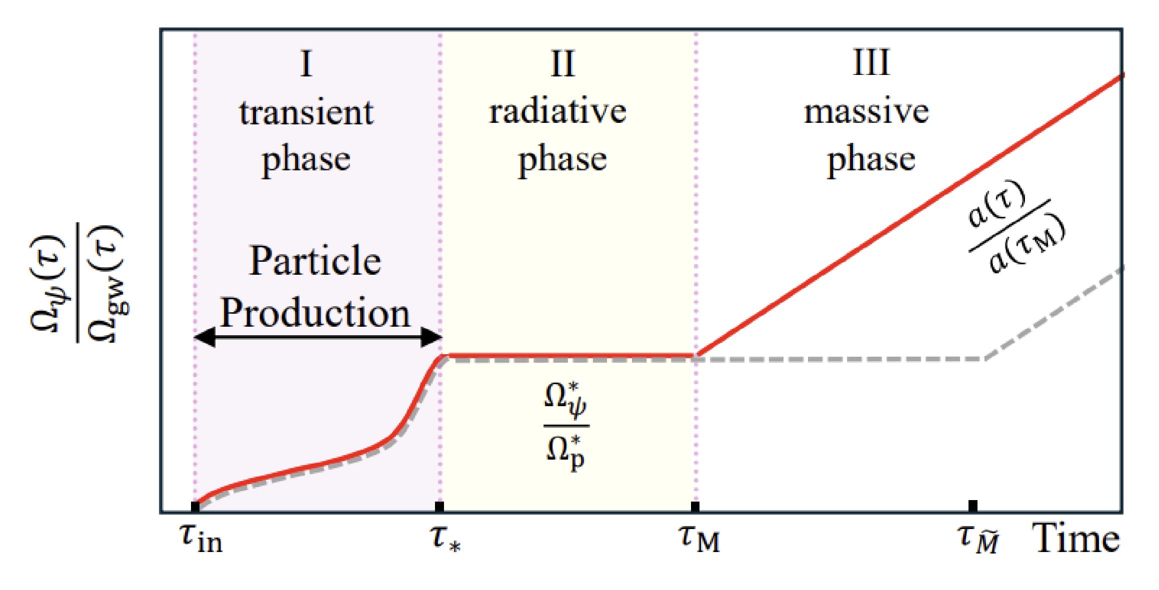
$$n_A(q) \approx \begin{cases} \mathcal{N}_{\rm p}(q)\, q_{\rm p}^3 \left(\frac{q}{q_{\rm p}}\right)^{m-1} & q_{\rm min} < q < q_{\rm p}, \\ \mathcal{N}_{\rm p}(q)\, q_{\rm p}^3 \left(\frac{q}{q_{\rm p}}\right)^{-n-1} & q_{\rm p} < q < q_{\rm max}, \end{cases}$$

$$\mathcal{N}_{\rm p}(q) = -\frac{\Omega_{\rm p}}{16}\left(\frac{H_0\,\beta}{a_{\rm in}\, q_{\rm p}^2}\right)^2\left[2b_\chi + (1+b_\chi^2)\chi(q)\right].$$

Fermion Energy Density

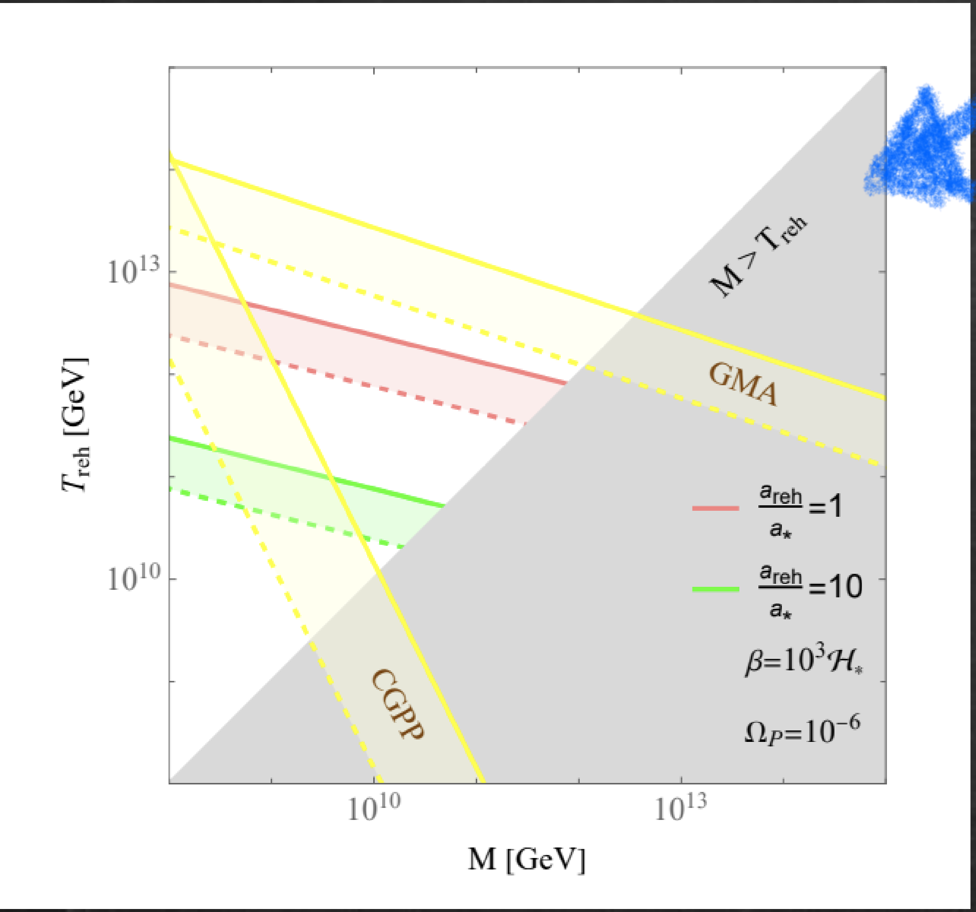
$$\nabla_\mu J^\mu_A = \frac{N_\chi}{24(4\pi)^2}\langle R\tilde{R}\rangle,$$





DM and Leptogenesis

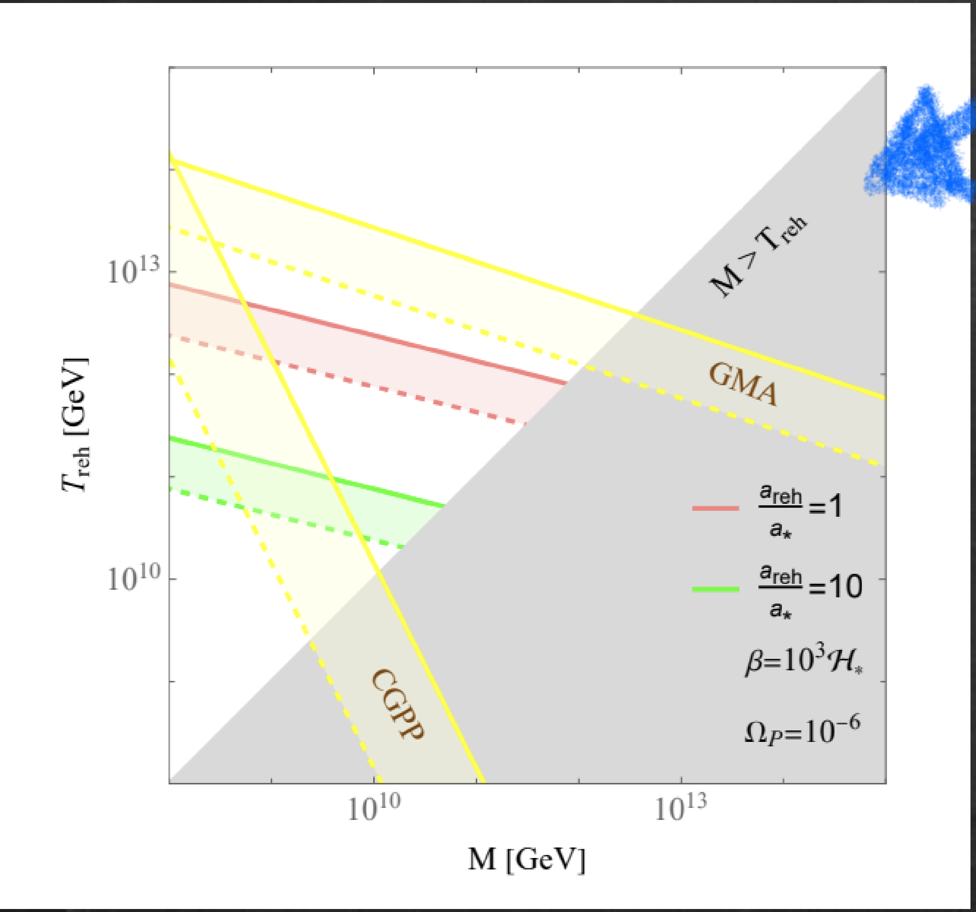
$$\nabla_\mu J^\mu_A = \frac{N_\chi}{24(4\pi)^2}\langle R\tilde{R}\rangle,$$



Gravitational ABJ Dark Matter

DM and Leptogenesis

$$\nabla_\mu J^\mu_A = \frac{N_\chi}{24(4\pi)^2}\langle R\tilde{R}\rangle,$$



Gravitational ABJ Dark Matter

Gravitational ABJ Leptogenesis

$T_{\rm reh} \sim 10^{14}{\rm GeV}$

$\Omega_{\rm p} \sim 10^{-6}$

Summary

Gravity and Quantum Effects in Cosmology can still surprise us:
We discussed an effect that is zero at tree level and non-zero at 1-loop in cosmic perturbations!

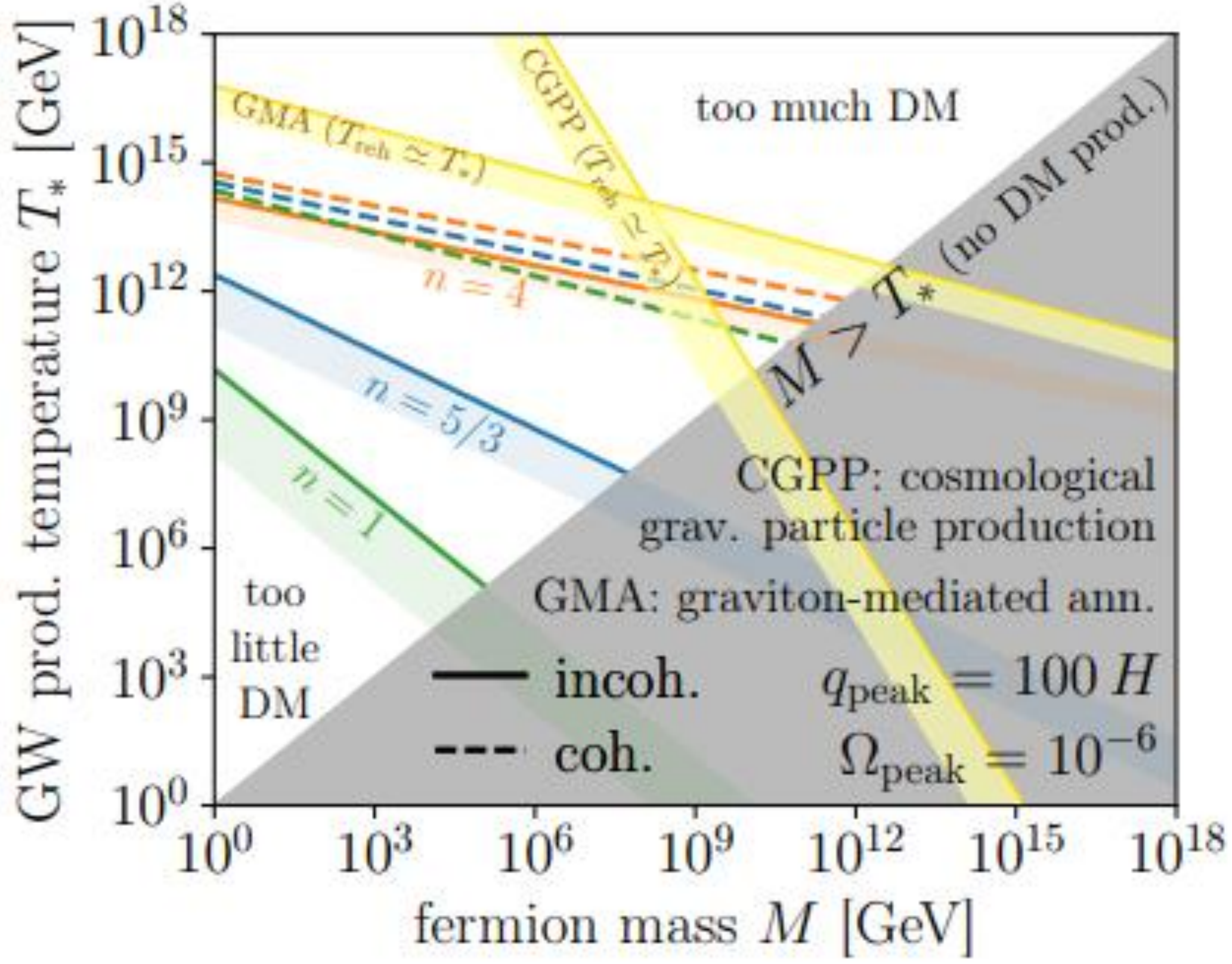
Cosmic Perturbations (like GWs) naturally break the conformal symmetry of Weyl Fermions in Cosmology

It leads to a new mechanism for dark matter production and baryogenesis in early universe.

Questions?!

Parameter space of GW-induced freeze-in of fermion

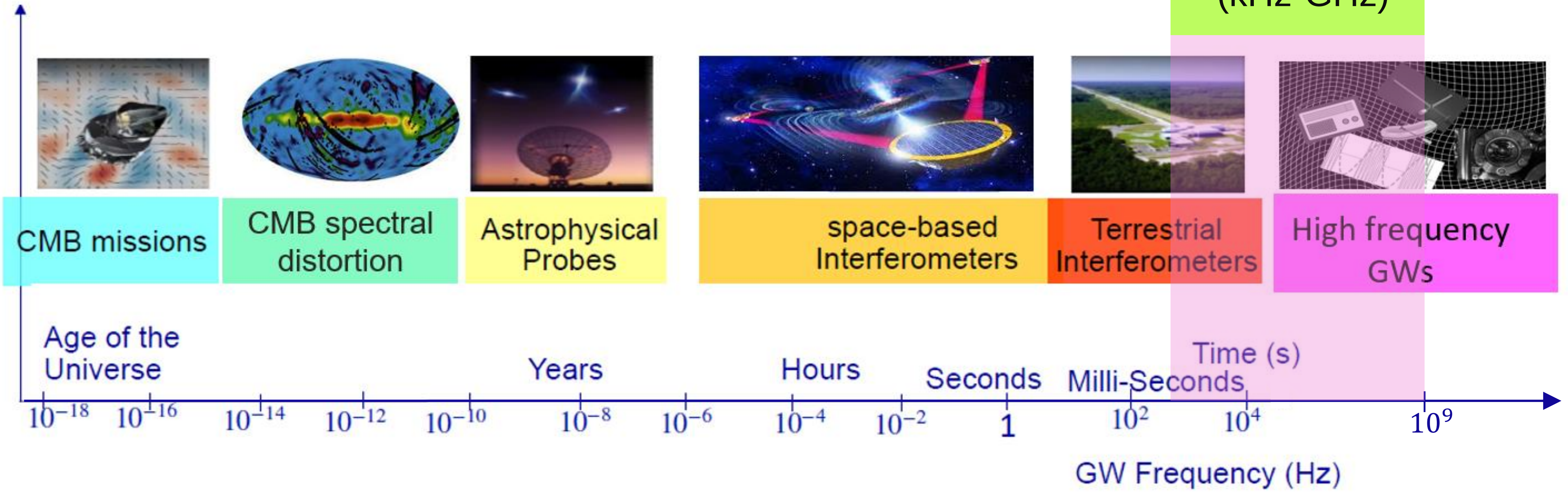
A.M. & Kopp 2024



Gravitational Waves Spectrum

GW-induced freeze-in mechanism requires a GWs spectrum with peak frequency

$\mathbf{f_{peak}} \in$ (kHz-GHz)



Age of the Universe = Billions of Years

Scalar number density for minimal coupling

$$\frac{a^3 n_k}{a_e^3 H_e^3} \approx \begin{cases} \frac{1}{8\pi^2}\tilde{m}^{-1}\tilde{k}^0 & 0 < \tilde{k} < \tilde{m}^{1/3} \\ \frac{1}{8\pi^2}\tilde{k}^{-3} & \tilde{m}^{1/3} < \tilde{k} < \frac{m_\varphi \kappa}{H_e} \\ C\tilde{k}^{-3/2} & \frac{m_\varphi \kappa}{H_e} < \tilde{k} < \tilde{a}_{\rm RH}\frac{m_\varphi \kappa}{H_e} \end{cases} ,$$