Large Infrared Fluctuations from Inflation: Dark Matter and GW Signatures

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Astroparticle Symposium, 2025@Institut Pascal

A. Chakraborty, S, Maiti, DM, Phys.Rev.D 111 (2025) 8, 083505;
A. Chakraborty, S. Clery, Md R. Haque, DM, Y. Mambrini; 2503.21877 (accepted in PRD)
A. Chakraborty, DM, R. Mondal; 2506.02141,
A. Chakraborty, DM, R. Mondal; 2508.XXXX,

In Collaboration with: A. Chakraborty, R. Mondal, S. Maiti, R.Haque, S. Clery, Y. Mambrini

IIT Guwahati

Our main message of this talk

In the particle DM description:

* If inflation is part of the standard model cosmology, universal Inflationary Infrared Modes alter DM parameter space significantly

OR

* The conventional phenomenological approach may not capture complete picture of DM physics if SM cosmology includes inflation

Y. Ema et al, JHEPÂ 07, (2019), 060;
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* If inflation is part of the standard model cosmology, universal Inflationary Infrared Modes alter DM parameter space significantly

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Out of many questions:

What role does inflation play on DM physics?
What are associated GW signatures?

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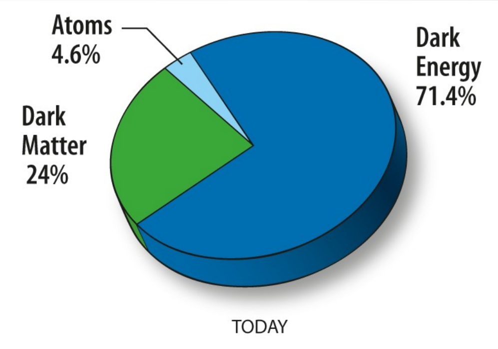
Given the inflationary phase:
What do we observe long after (today)?

Inflation

Stable massive particles/objects (DM, PBH+all)

SM massless particles (radiation), Large scale magnetic field

CMB fluctuation, GW



Today: Background + Fluctutations

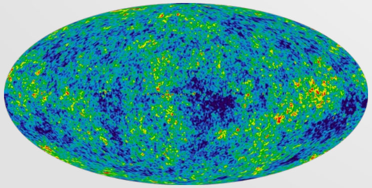
Extremely homogeneous Universe

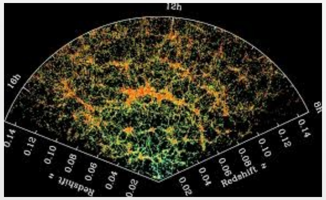
Many more...

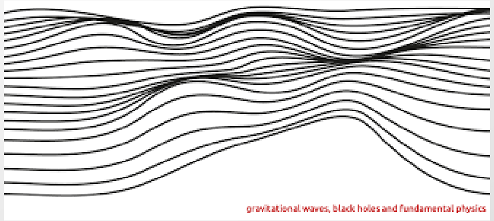
CMB

Visible and Dark Matter

GW







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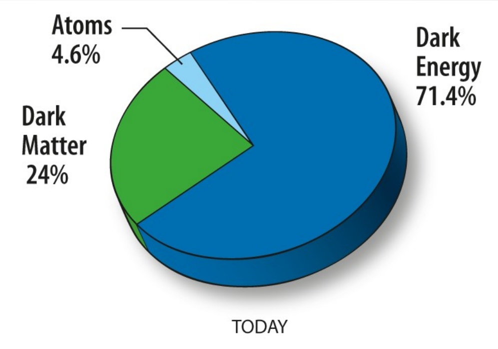

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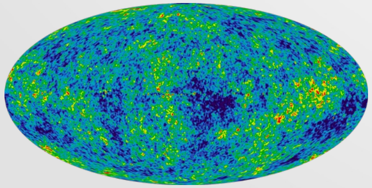

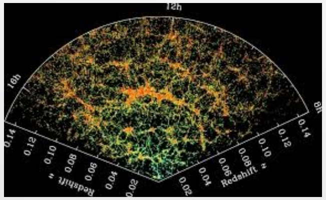

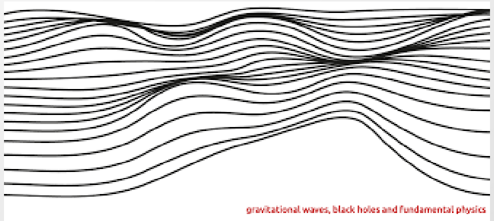

Given the inflationary phase:

What do we observe long after (today)?

Inflation

Quantum mechanical particle production

Non-gravitational

$$\boxed{g_1 \phi s^3, g_2 \phi^2 s^2, h \phi \bar{f} f \ldots}$$

Stable massive particles/objects (DM, PBH+all)

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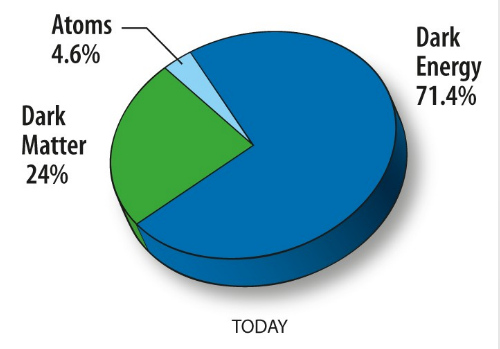

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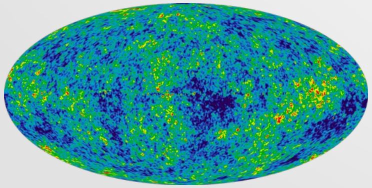
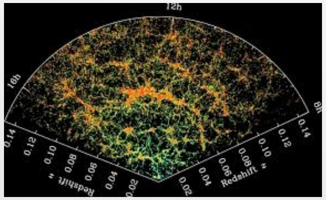
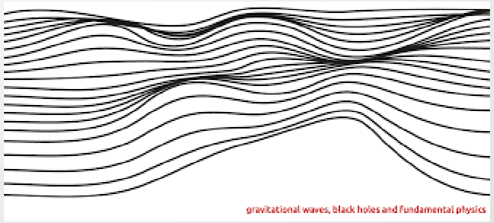


Visible and Dark Matter



GW



Given the inflationary phase:
What do we observe long after (today)?

Inflation

Quantum mechanical particle production

Non-gravitational

$$g_1\phi s^3, g_2\phi^2 s^2, h\phi\bar{f}f\ldots$$

Universal (gravitational)

$$\sim \frac{1}{M_P} h_{\mu\nu} T_i^{\mu\nu}, i=s, f, DM, \phi$$

Stable massive particles/objects (DM, PBH+all)

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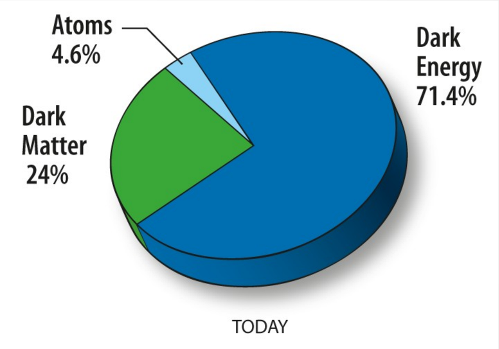

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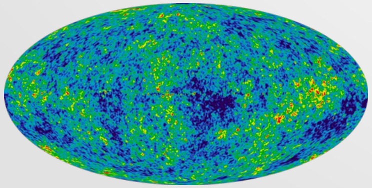
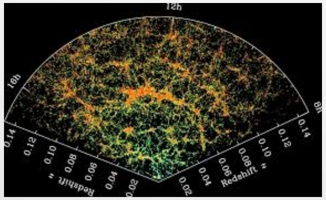
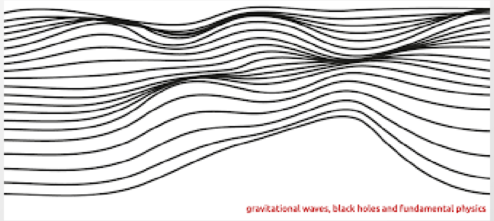
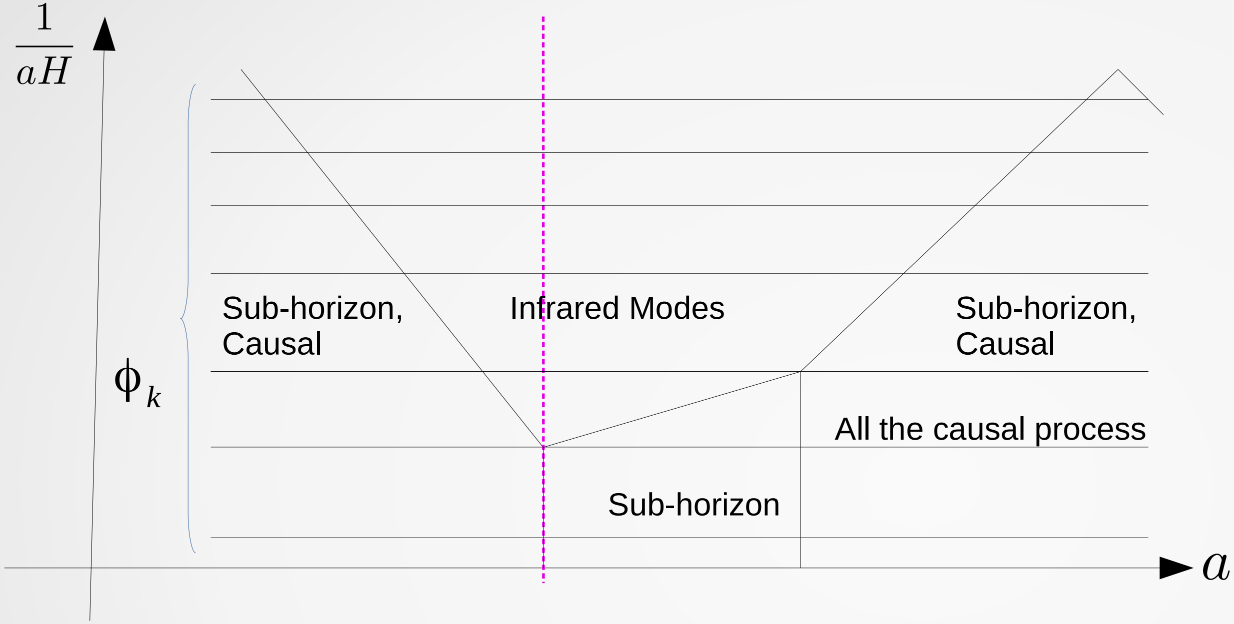




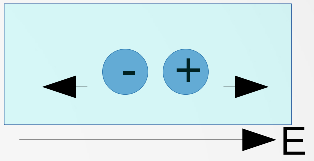


$b_k|0\rangle = 0$

Inflationary particle production



Similar to Schwinger pair production in E-field



Stong E-field accelerating particles to energies > mass over a distance smaller than Compton wavelength of the particle,

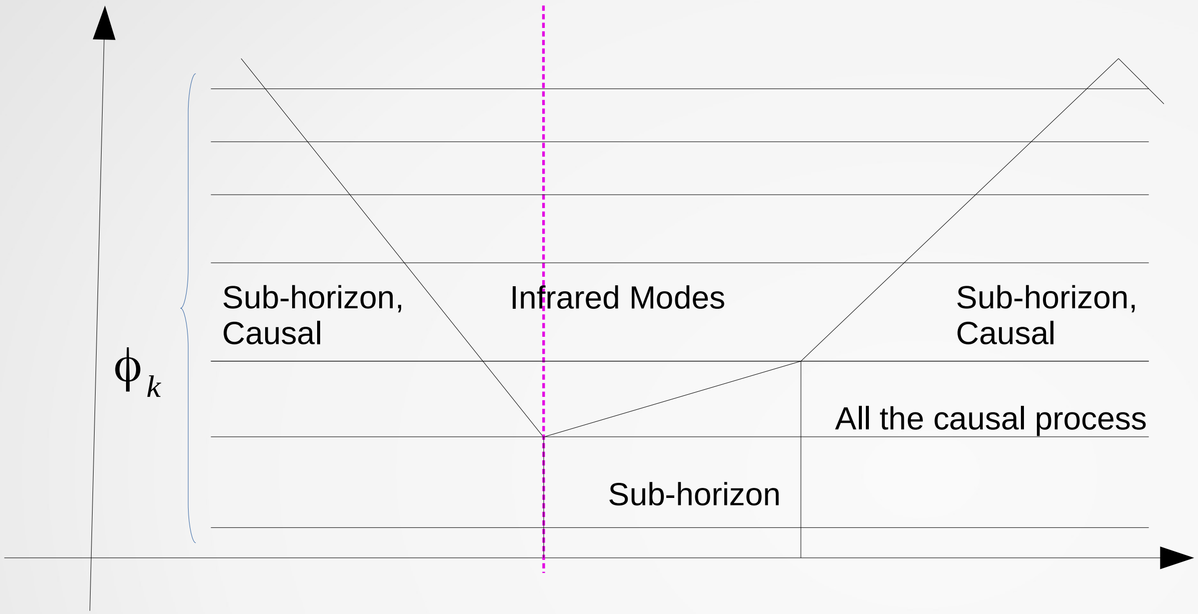
Minimal setting

Inflaton + SM + DM

E.W. Kolb and A. Long, arXiv:2312.09042

$b_k|0\rangle = 0$

Basics of Inflationary particle production



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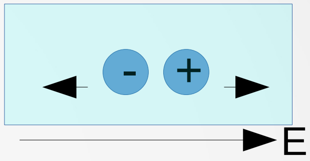

Stong E-field accelerating particles to energies > mass over a distance smaller than Compton wavelength of the particle,

$$\ddot{\phi}_k + \omega^2(k,\eta)\phi_k = 0$$

$b_k|0\rangle = 0$

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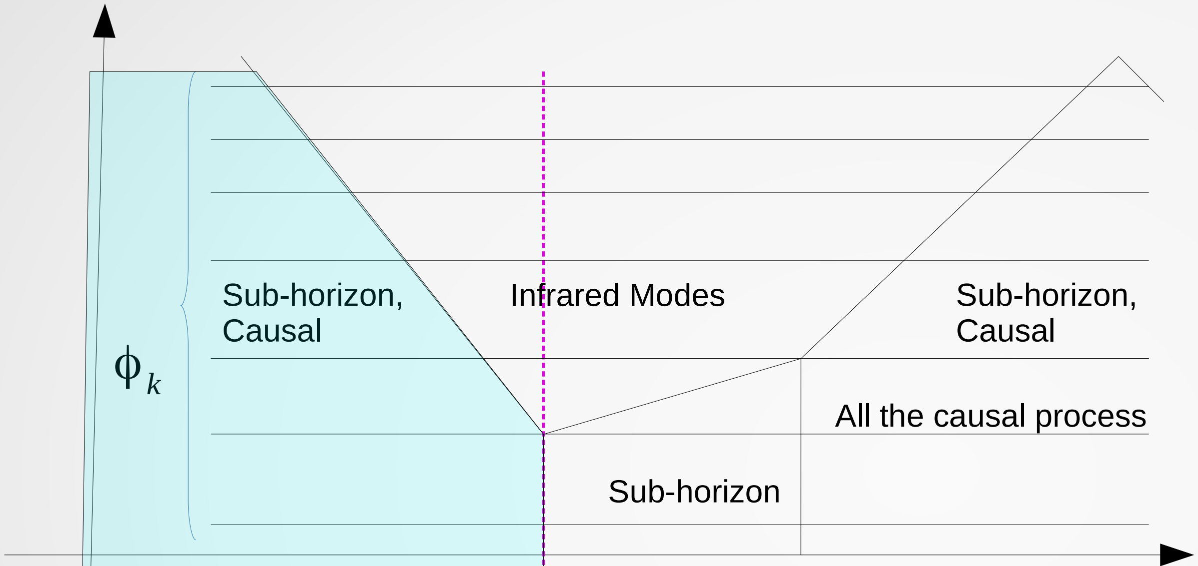

$$\eta \to -\infty$$

$$\phi_k = a_k \psi_k + a_k^\dagger \psi^*$$

$$\phi_k = \frac{1}{\sqrt{2k}} e^{-\int w(\eta')d\eta'}$$

$$a_k|0\rangle_{\mathrm{BD}} = 0$$

Adiabatic vacuum

$$\ddot{\phi}_k + \omega^2(k,\eta)\phi_k = 0$$

E.W. Kolb and A. Long, arXiv:2312.09042

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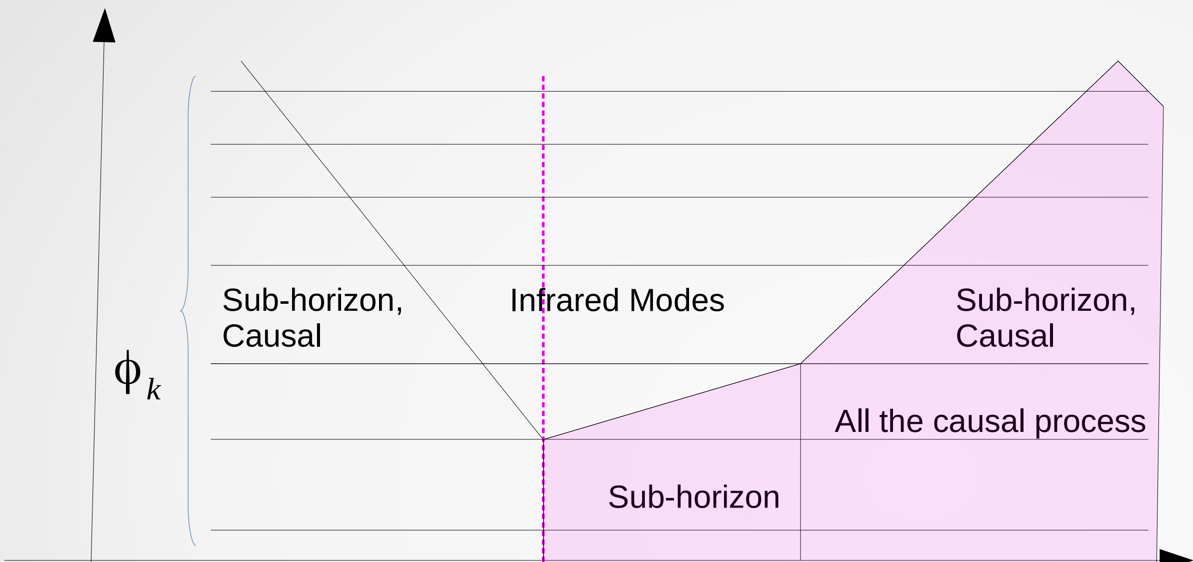

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Adiabatic vacuum

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Comoving wave number k should admit a particle description

i) When the mode evolution is adiabatic,

ii) When the modes are inside the horizon,

iii) When the modes are oscillatory.

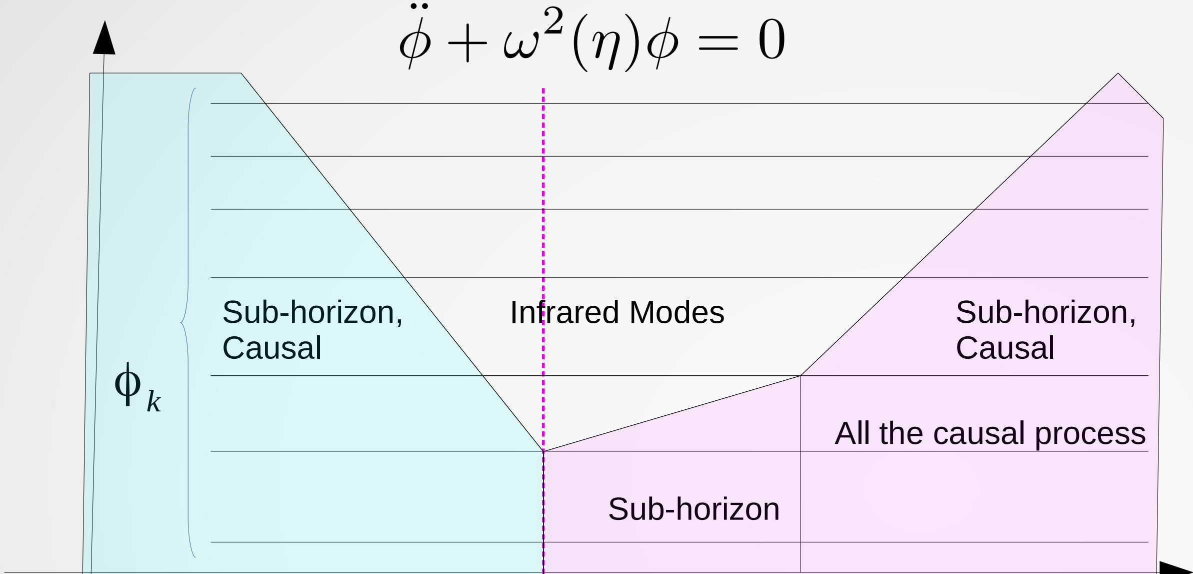
At intermediate times, a particle description may not be appropriate

E.W. Kolb and A. Long, arXiv:2312.09042

$b_k|0\rangle = 0$

Basics of Inflationary particle production

$$\ddot{\phi} + \omega^2(\eta)\phi = 0$$



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Adiabatic vacuum

Bogoliubov transformation

$$b_k = \alpha_k a_k + \beta_k^* a_k^\dagger$$

$$|\alpha_k|^2 - |\beta_k|^2 = 1$$

Comoving number density

$$|\beta_k|^2 = f(k,\eta) = \langle b_k^\dagger b_k \rangle_{\rm BD}$$

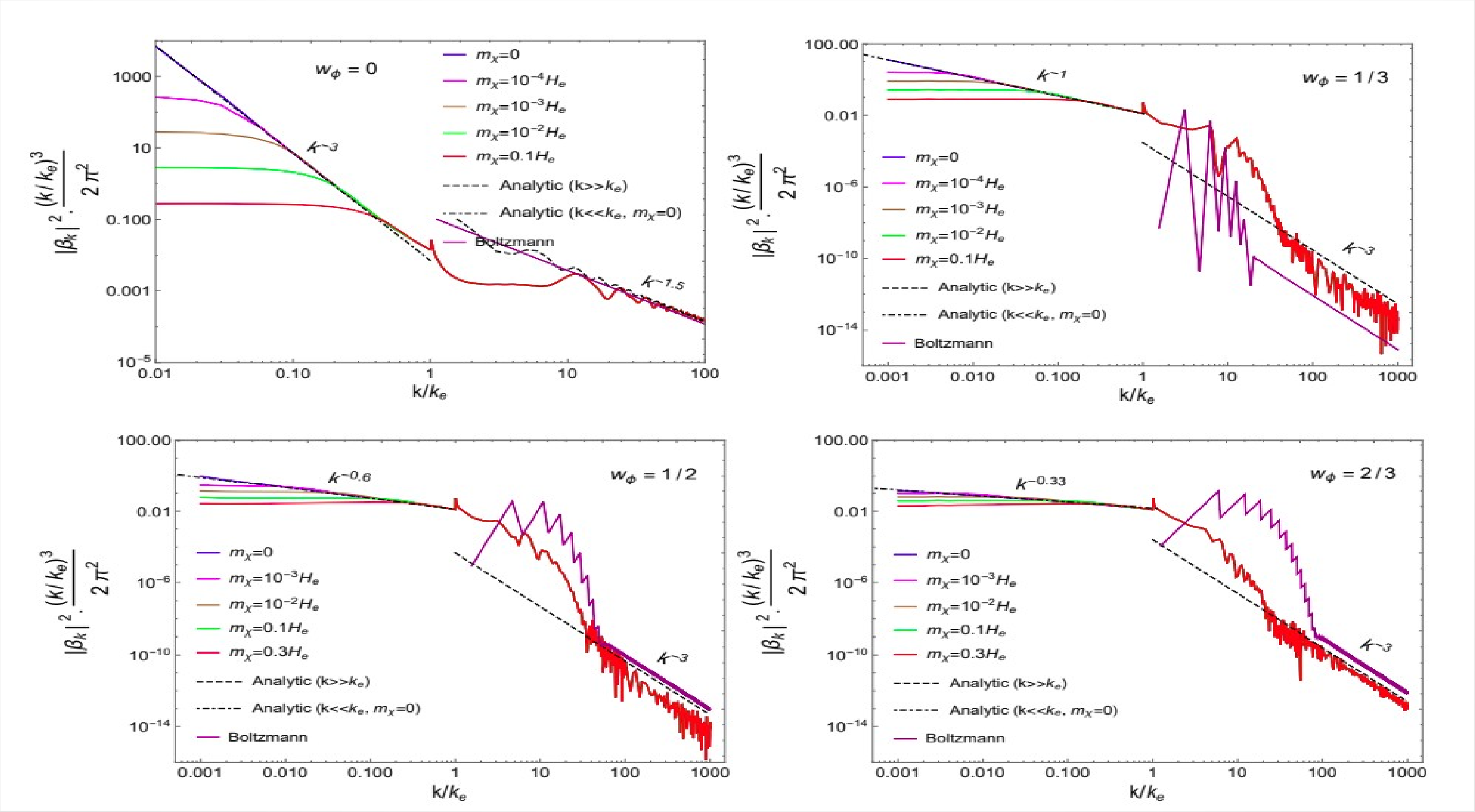
$$a^3 n = \int \frac{d^3k}{(2\pi)^3} \langle b_k^\dagger b_k \rangle_{\rm BD}$$

Number density is defined once scales reenter the horizon

E.W. Kolb and A. Long, arXiv:2312.09042

Typical form of the full spectrum $|\beta_{\mathbf{k}}|^2$

For massive scalar DM field



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Typical form of the Infrared spectrum

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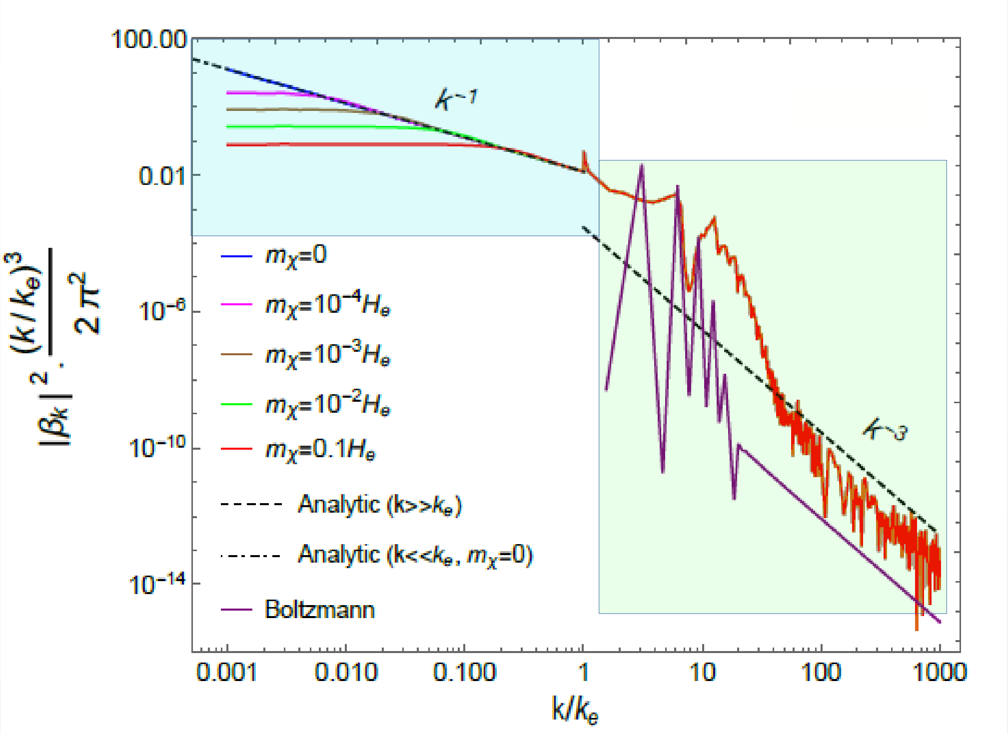
For massive scalar DM field

$$|\beta_k|^2 \approx \frac{e^{-\frac{\pi H_e}{4m_\chi}\left(\frac{k}{k_e}\right)^2}}{\sqrt{m_\chi/H_e}}\left(\frac{k}{k_e}\right)^{\delta}$$

We assume simple form for our discussion



Well-studied example: Inflationary quantum fluctuations:

Leading to inhomogeneities in CMB and LSS of the Universe.

Typical form of the Infrared spectrum

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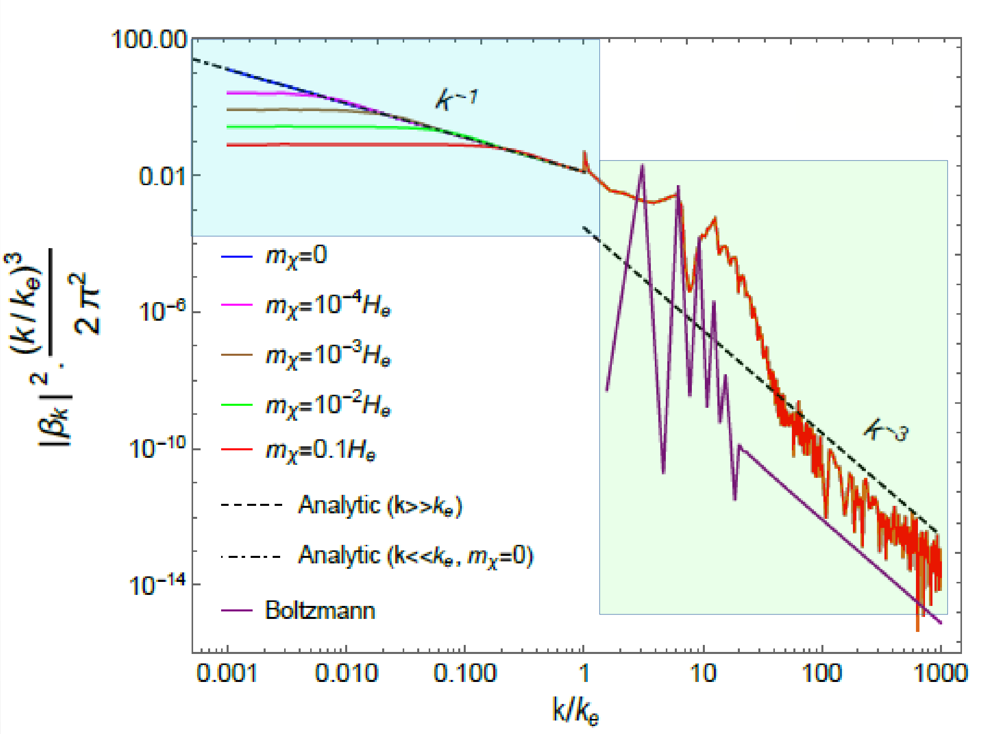
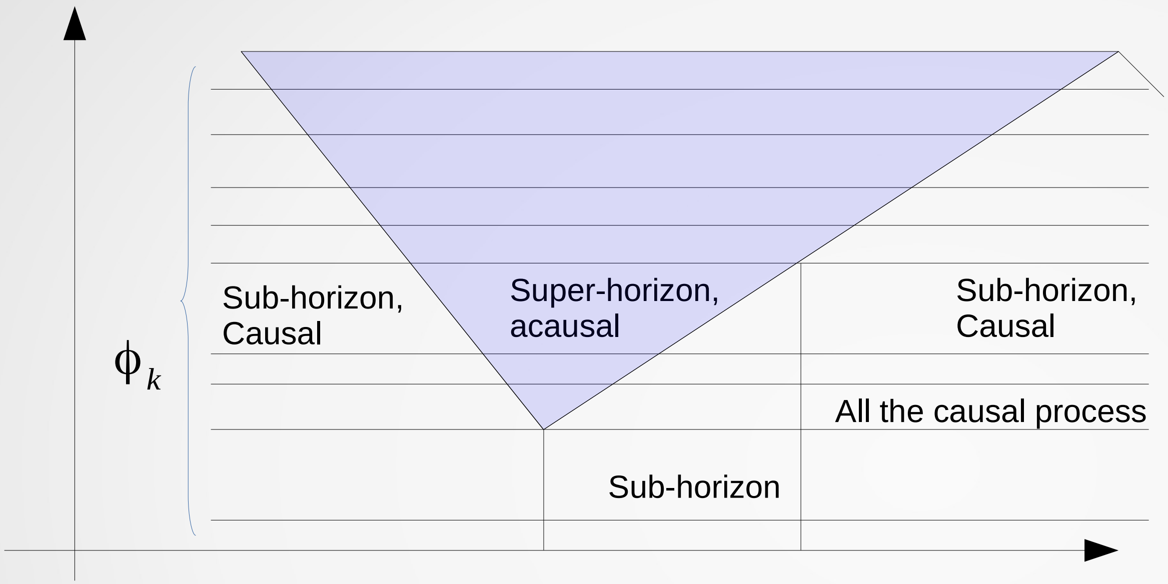


Two possibilites

i) DM can be completely dark

ii) If not, how does the existing phenomenology change?

DM being completely Dark



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Instantaneous reheating

Deffining IR production rate

Boltzmann Equation

$$\dot{n}_\chi + 3Hn_\chi = \underbrace{\frac{1}{a^3}\frac{d}{dt}\left(\int_{a(t)H(t)}^{k_{\rm end}} \frac{d^3k}{(2\pi)^3}|\beta_k|^2\right)}_{Q_{\rm IR}}$$

DM number density:
When modes are inside the horizon

DM being completely Dark

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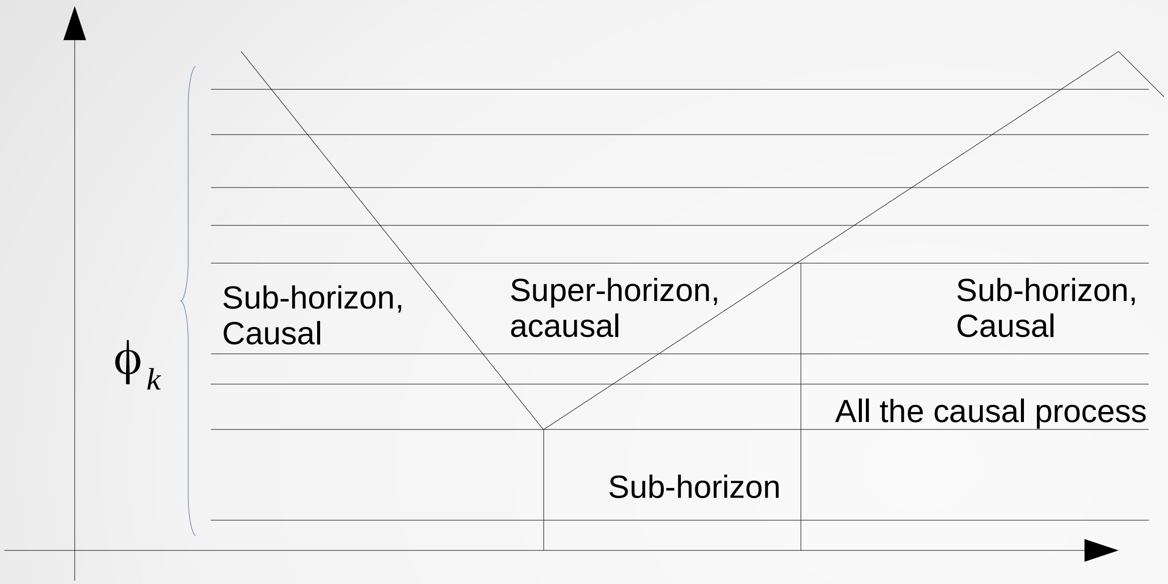

Instanteneous reheating

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Infrared Gravitational DM

Boltzmann Equation

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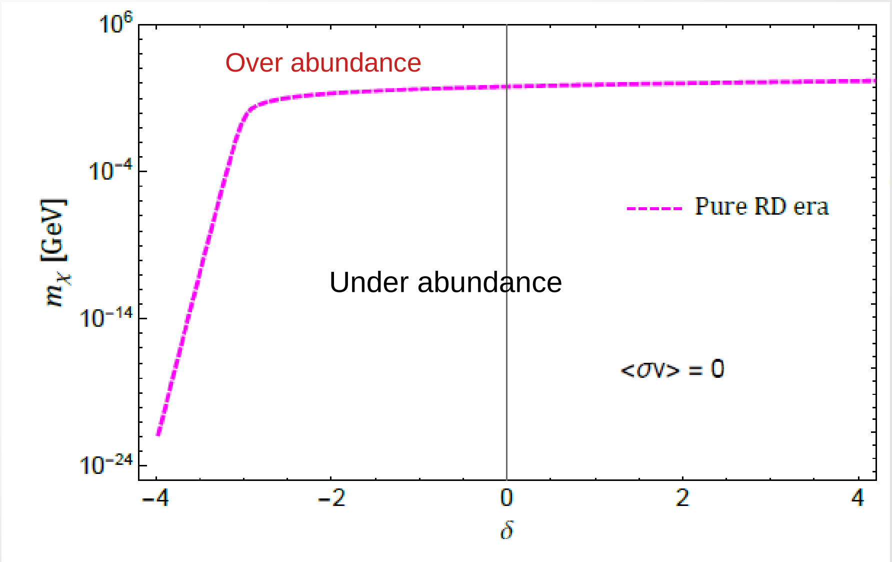
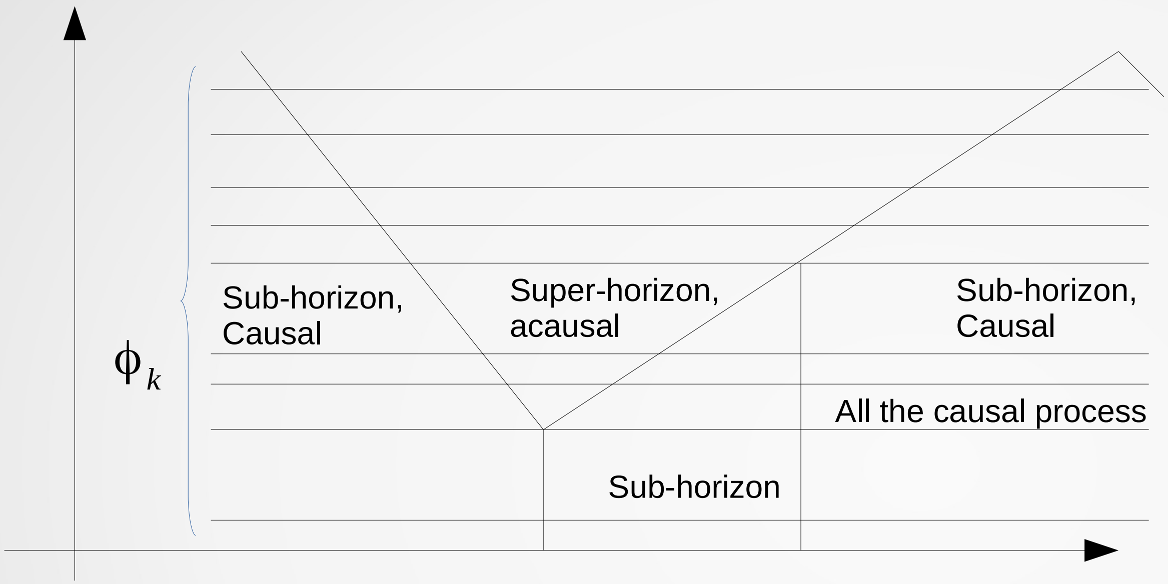


Not completely dark



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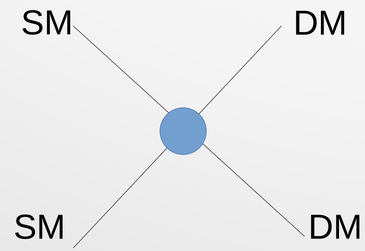
Conventional + Infrared
Gravitational contribution

Boltzmann Equation

$$\dot{n}_\chi + 3 H n_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_\chi^{\mathrm{eq}\;2} \right) + \frac{1}{a^3} \frac{d}{dt} \left(\int_{a(t)H(t)}^{k_{\mathrm{end}}} \frac{d^3 k}{(2\pi)^3} |\beta_k|^2 \right)$$



+

Infrared DM Injection

Not completely dark

Modified Boltzmann Equation

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_\chi^{\mathrm{eq}\ 2}\right) + \frac{1}{a^3}\frac{d}{dt}\left(\int_{a(t)H(t)}^{k_{\mathrm{end}}} \frac{d^3k}{(2\pi)^3}|\beta_k|^2\right)$$

Freeze-in

Freeze-out

Not completely dark

Modified Boltzmann Equation

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Freeze-in

$$\Omega_\chi h^2 = \left(\frac{\langle\sigma v\rangle T_{\mathrm{re}}^3}{\pi^2 H_{\mathrm{e}}} + \frac{\mathcal{A}H_{\mathrm{e}}^{7/2}}{4\,T_{\mathrm{re}}^3\sqrt{m_\chi}}\left(\frac{4m_\chi}{\pi H_{\mathrm{e}}}\right)^{\frac{3+\delta}{2}}\Gamma\left[\frac{3+\delta}{2}\right]\right) \times \left(\frac{m_\chi}{5.9\times 10^{-7}\,\mathrm{GeV}}\right)$$

Instantaneous reheating: $T_{\mathrm{re}} \approx 10^{15}\ \mathrm{GeV}$.

Not completely dark

Modified Boltzmann Equation

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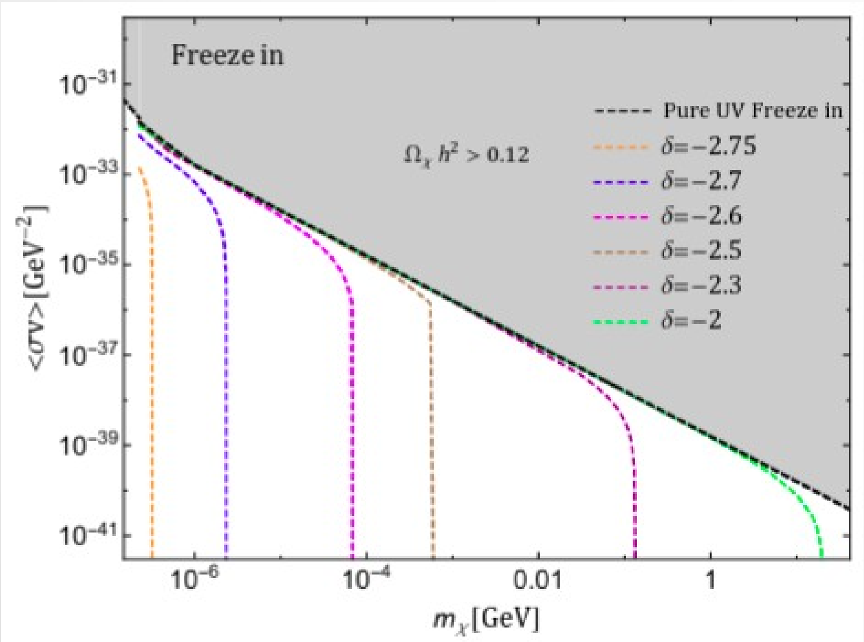
Freeze-in



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Not completely dark

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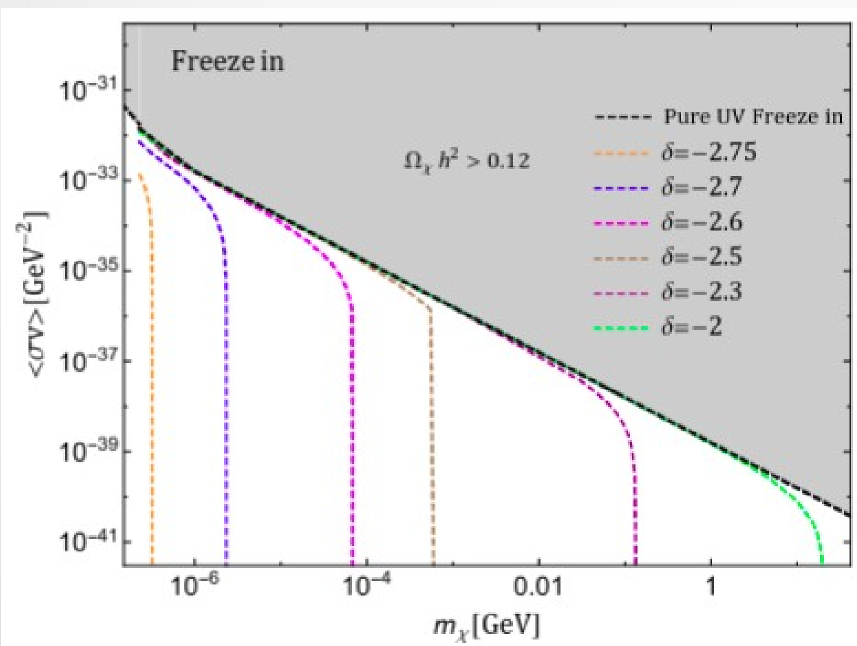

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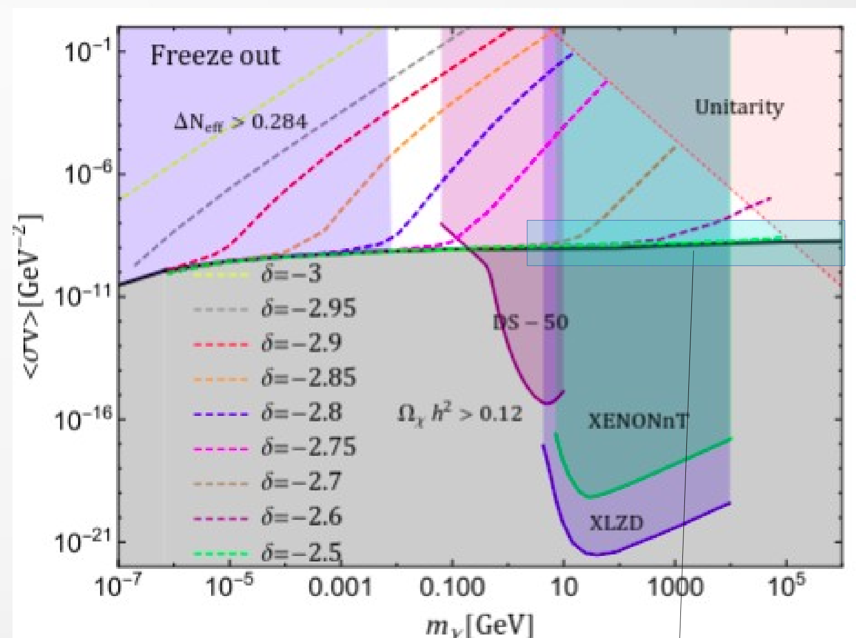

WIMP miracle

Not completely dark

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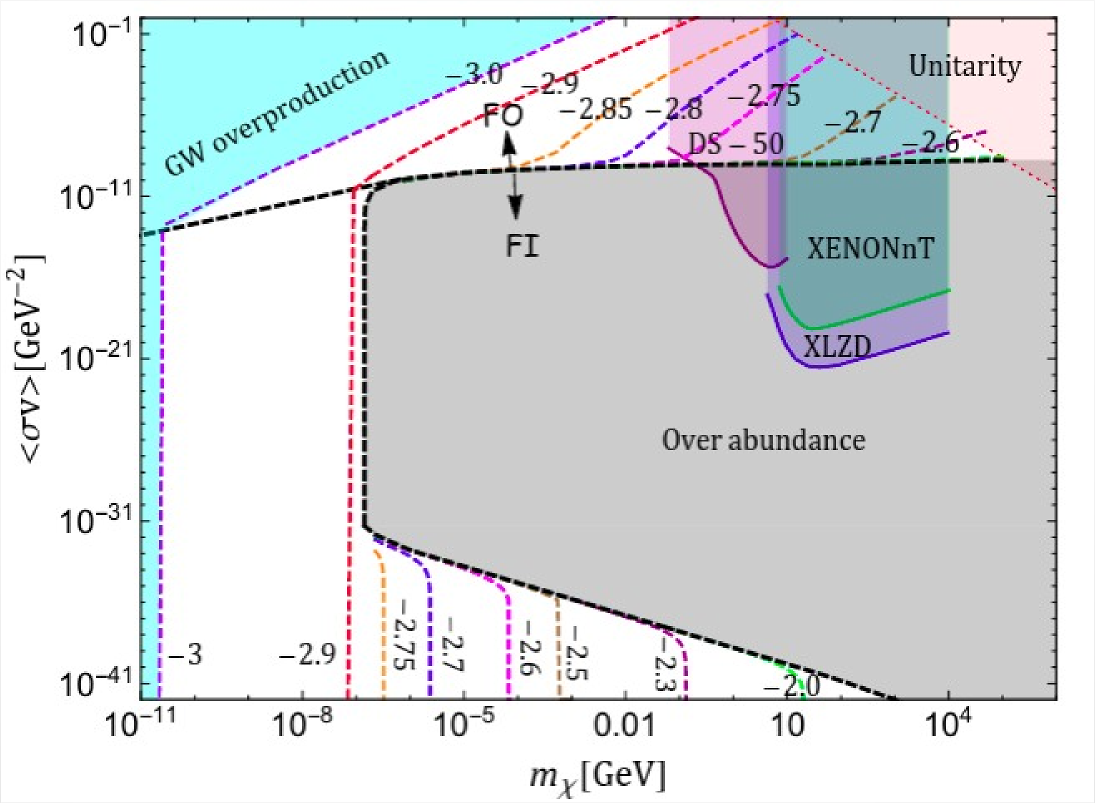
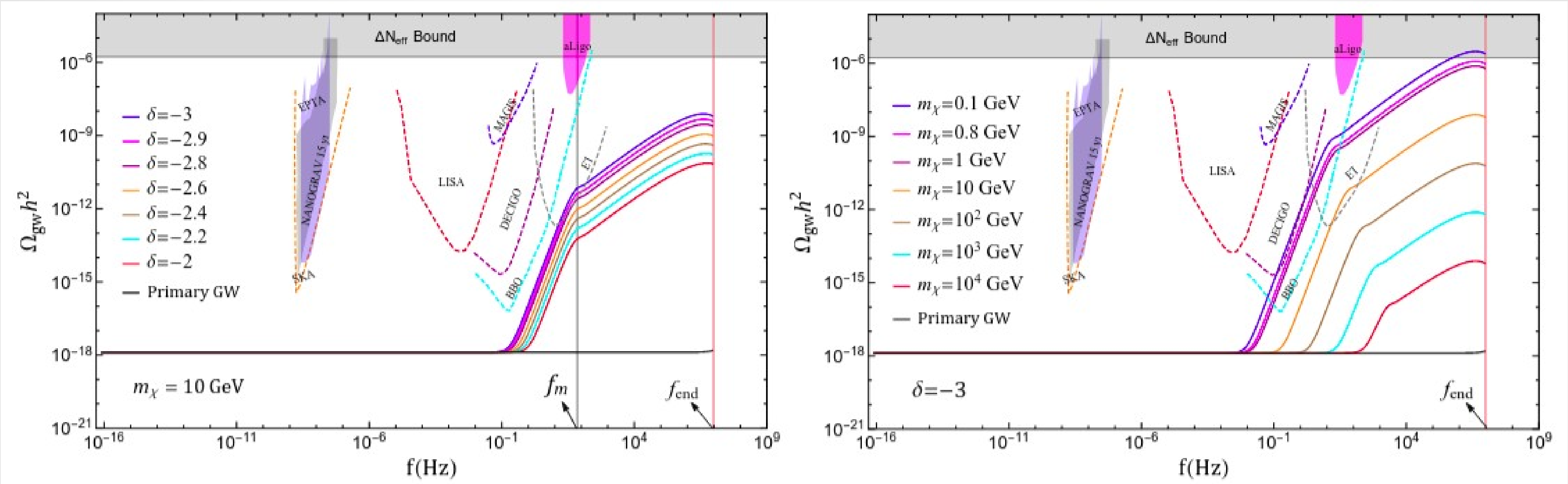
Freeze-out

Freeze-in



Gravitational wave signatures



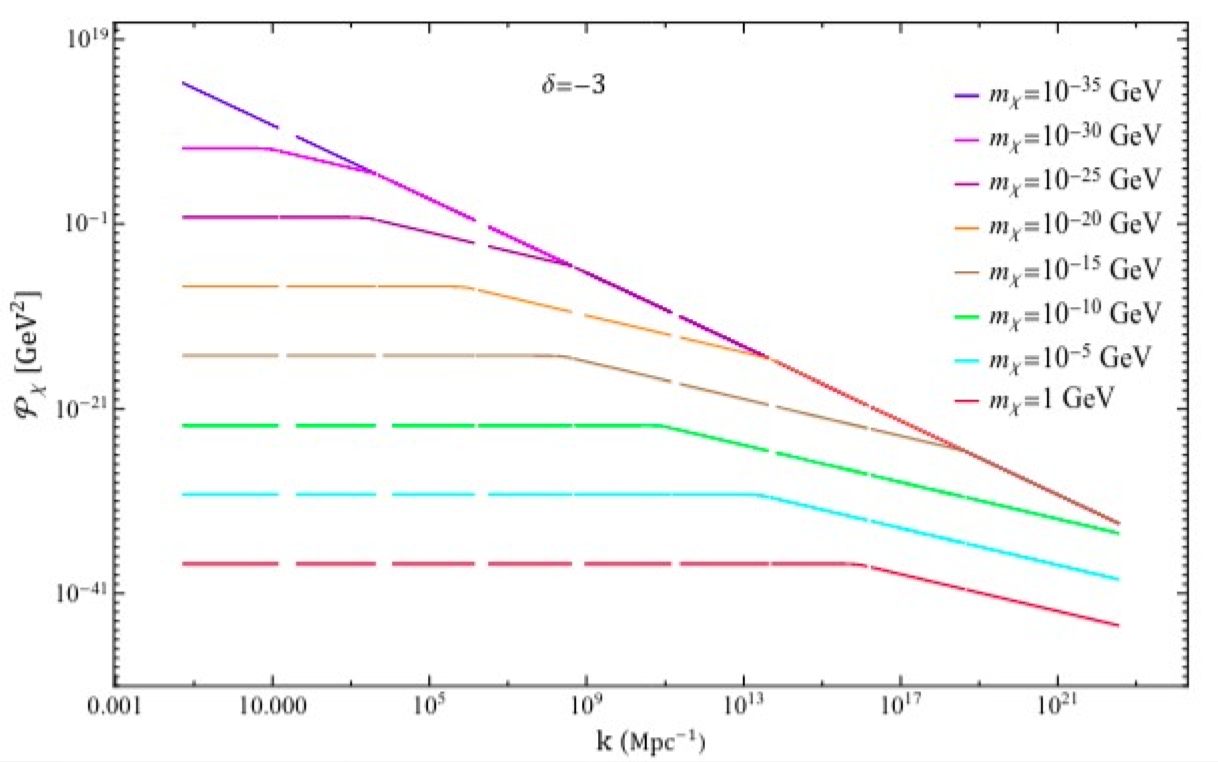
Conclusions and future directions

- Inflationary infrared modes are universal
- They can dominate over the course of universe evolution
- If those fluctuations are of DM, they significantly impact the standard phenomenology
- They also carry distinct GW signatures

1. What is the impact of reheating?
2. How do their perturbations evolve?
3. ...

Detailed scalar spectrum

$$\mathcal{P}_\chi(k,\eta) = \frac{k^3}{2\pi^2}|X_k^{\rm RD}|^2 = \left(\frac{k_{\rm e}^2}{4\sqrt{2}\,\pi^3}\right)\mathcal{B}(\delta)\begin{cases} \frac{\pi}{\Gamma^2(3/4)}\left(\frac{H_{\rm e}}{m_\chi}\right)^{3/2}\left(\frac{1}{\eta\,k_{\rm e}}\right)\frac{e^{-\frac{\pi k^2}{4a_{\rm e}^2 H_{\rm e} m_\chi}}}{(k/k_{\rm e})^{-(3+\delta)}} & \text{for } \frac{k}{k_{\rm e}} < \sqrt{\frac{m_\chi}{H_{\rm e}}} \\ \left(\frac{H_{\rm e}}{m_\chi}\right)\left(\frac{1}{\eta\,k_{\rm e}}\right)\left(\frac{k_{\rm e}}{k}\right)^{(2+\delta)} & \text{for } \sqrt{\frac{m_\chi}{H_{\rm e}}} \le \frac{k}{k_{\rm e}} < \bar{a}_{\rm RD}\frac{m_\chi}{H_{\rm e}} \\ \left(\frac{k_{\rm e}}{k}\right)^{(1+\delta)} & \text{for } \frac{k}{k_{\rm e}} \ge \bar{a}_{\rm RD}\frac{m_\chi}{H_{\rm e}} \end{cases}$$



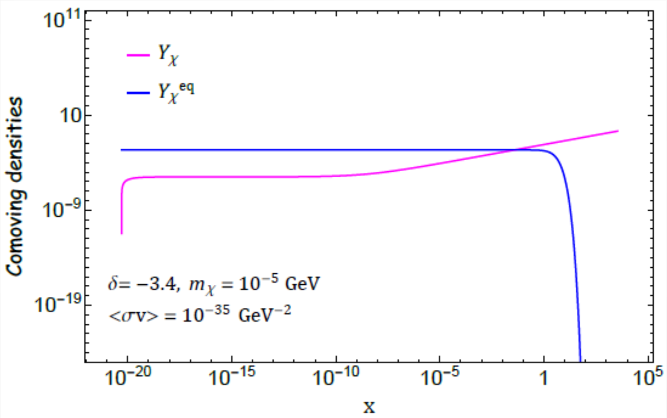
$\phi(t)$

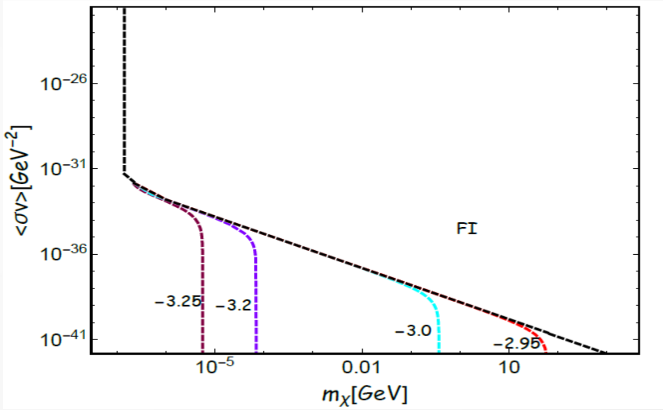
Not completely dark

Modified Boltzmann Equation

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_\chi^{\text{eq}\;2}\right) + \frac{1}{a^3}\frac{d}{dt}\left(\int_{a(t)H(t)}^{k_{\text{end}}} \frac{d^3k}{(2\pi)^3}|\beta_k|^2\right)$$

Freeze-in





WIMP miracle

Freeze-out