16/09/23

Scalars 2023

An opportunity to discuss various aspects of scalar particles.

Inflationary and Post-Inflationary Scalar Dark Matter Production

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+ Mathias Pierre (DESY) and Sarunas Verner (Florida)

2206.08940, 2303.07359, 2305.14446

Universidad Nacional Autónoma de México

CONAHCYT
CONSEJO NACIONAL DE HUMANIDADES CIENCIAS Y TECNOLOGÍAS

INSTITUTO DE FÍSICA
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1. Dark Matter

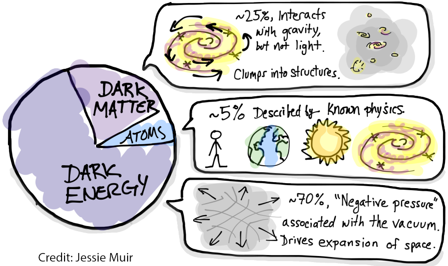
2. Inflation

3. Production

4. Limits

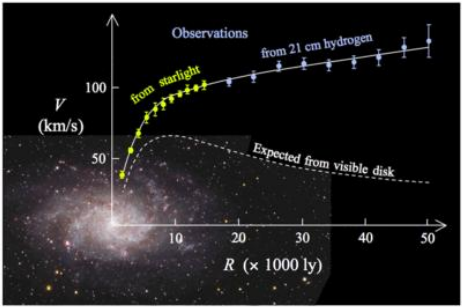
5. Prospects

Dark Matter



Credit: Jessie Muir

galaxy rotation



collisions of clusters

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2. Inflation

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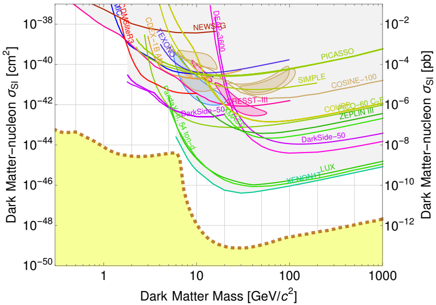
4. Limits

5. Prospects

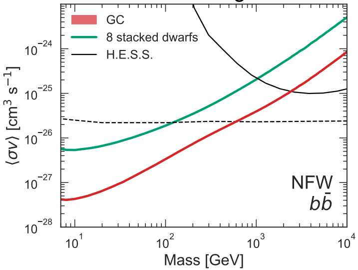
Non-gravitational detection

direct detection



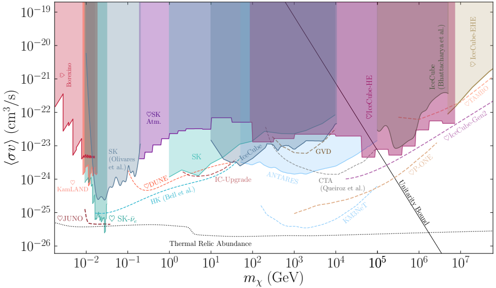
SuperCDMS Dark Matter Limit Plotter

annihilations in the galactic core



K. Abazajian et al., PRD 102 (2020), 043012 (Fermi-LAT)

annihilations to neutrinos



C. Argüelles et al., arXiv:1912.09486 [hep-ph]

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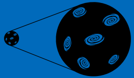

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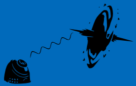
4. Limits



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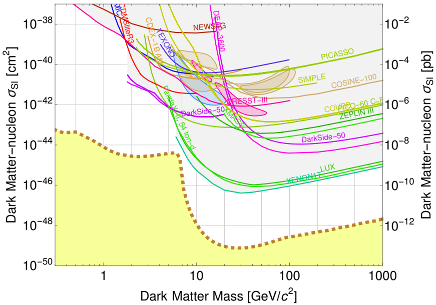

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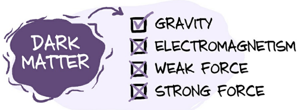

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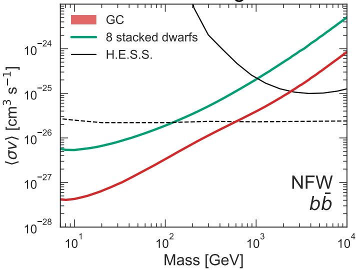

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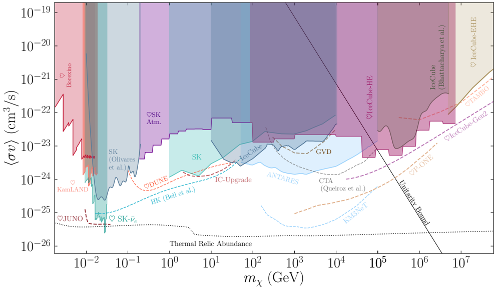
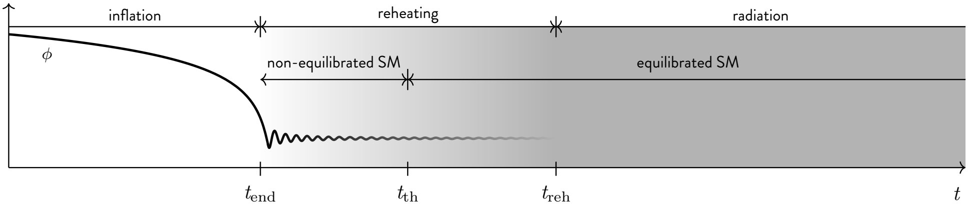


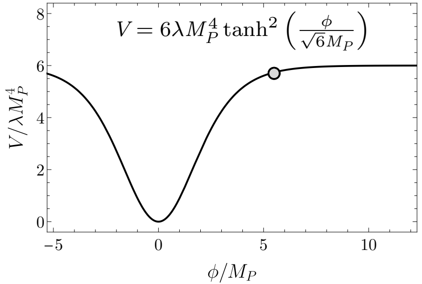
C. Argüelles et al., arXiv:1912.09486 [hep-ph]

Inflation and reheating



Inflation: a slowly rolling scalar field in FRW, $ds^2 = dt^2 - a(t)^2\, d\mathbf{x}^2$

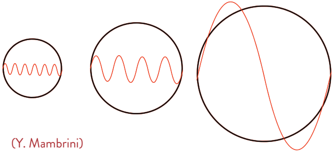
$$
\begin{aligned}
\ddot{\phi} + 3H\dot{\phi} + V'(\phi) &= 0 \\
H \equiv \frac{\dot{a}}{a} &= \left(\frac{\rho_\phi}{3M_P^2}\right)^{1/2} \\
\frac{1}{2}\dot{\phi}^2 + V(\phi) &= \rho_\phi \\
\frac{1}{2}\dot{\phi}^2 - V(\phi) &= p_\phi
\end{aligned}
$$



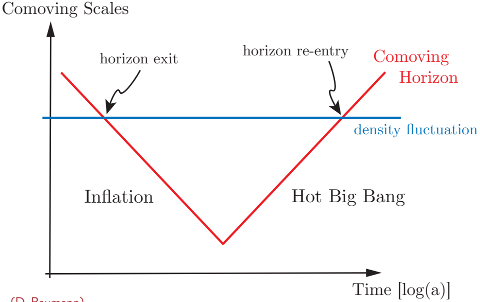
R. Kallosh and A. Linde, JCAP 10 (2013), 033

Primordial fluctuations

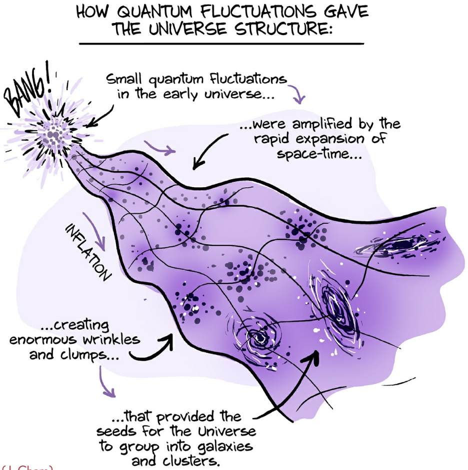
Quantum fluctuations in ϕ, g are stretched by the expansion



(Y. Mambrini)



(D. Baumann)



(J. Cham)

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2. Inflation
3. Production
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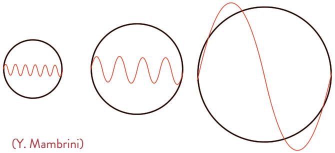
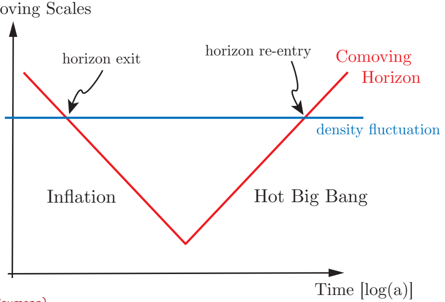


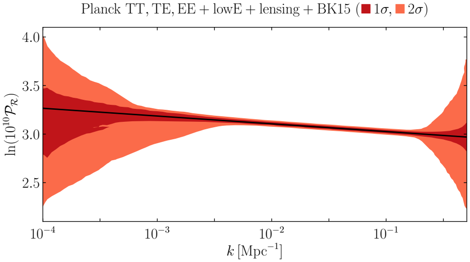
(Y. Mambrini)

Curvature: $\mathcal{R} = \frac{1}{2}\delta g^{00} + \frac{H}{\dot{\phi}}\delta\phi$

$$\langle \mathcal{R}(k)\mathcal{R}^*(k')\rangle = \frac{2\pi^2}{k^3}\mathcal{P}_{\mathcal{R}}\delta(k-k')$$



(D. Baumann)



Y. Akrami et al. [Planck], Astron. Astrophys. 641 (2020) A10

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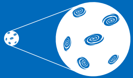

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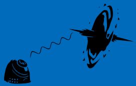

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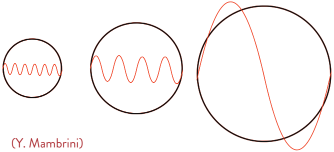
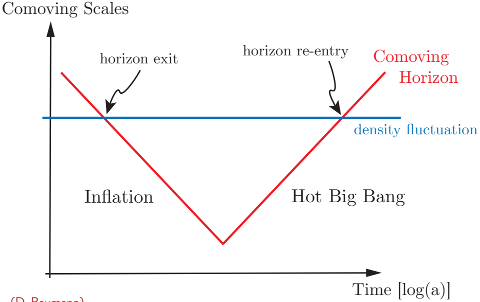


(Y. Mambrini)



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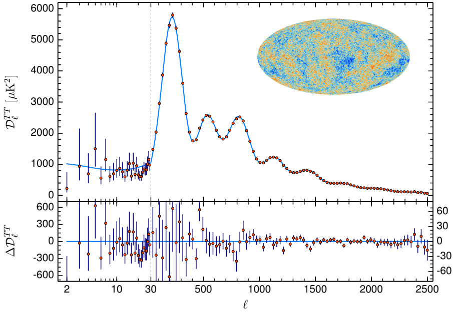
Curvature: $$\mathcal{R} = \frac{1}{2}\delta g^{00} + \frac{H}{\dot{\phi}}\delta\phi$$

T-fluctuations in the CMB



$$\mathcal{D}_\ell^{TT} = \frac{\ell(\ell+1)}{\pi^2}\int_0^\infty dk\, k^2 \mathcal{P}_\mathcal{R}(k)|\tilde{T}_\ell(k)|^2$$

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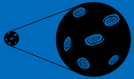

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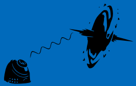

5. Prospects

Curvature and inflaton couplings

General relativity can be obtained from a stationary-action principle

$$\mathcal{S} = \int d^4x \sqrt{-g}\left[-\frac{1}{2}M_P^2 R + \mathcal{L}_{\rm SM}\right] \xrightarrow{\delta g_{\mu\nu}} R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} = 8\pi G T_{\mu\nu}^{(\rm SM)}$$

A simple DM model: scalar (spin 0) and only interacts with gravity and/or the inflaton

$$\mathcal{S} = \int d^4x \sqrt{-g}\left[-\frac{1}{2}(\overbrace{M_P^2}^{\text{Einstein-Hilbert term}} - \underbrace{\xi\chi^2}_{\text{non-minimal coupling}})R + \frac{1}{2}\underbrace{(\partial_\mu\chi)^2}_{\text{kinetic term}} - \frac{1}{2}\overbrace{m_\chi^2\chi^2}^{\text{mass term}} - \frac{1}{2}\underbrace{\sigma\phi^2\chi^2}_{\phi\text{-coupling}} + \cdots\right]$$

Non-minimal couplings are generated by quantum corrections even if they are not present in the classical action

QFT in the early universe

Introducing *conformal time*, $dt = a\, d\tau$, and the re-scaled field $X = a\chi$,

$$\left(\partial_\tau^2 - \nabla^2 + a^2 m_{\rm eff}^2\right) X \;=\; 0\,, \qquad m_{\rm eff}^2 \;=\; m_\chi^2 + \sigma\phi^2 + \frac{1}{6}(1-6\xi)R$$

Quantize as a superposition of oscillators

$$\hat{X}(\tau, \mathbf{x}) \;=\; \int \frac{d^3\boldsymbol{k}}{(2\pi)^{3/2}}\, e^{-i\boldsymbol{k}\cdot\mathbf{x}} \left[X_k(\tau)\,\hat{a}_{\boldsymbol{k}} + X_k^*(\tau)\,\hat{a}^\dagger_{-\boldsymbol{k}}\right]\,, \qquad [\hat{a}_{\boldsymbol{k}}, \hat{a}^\dagger_{\boldsymbol{k}'}] = \delta(\boldsymbol{k} - \boldsymbol{k}')\,, \quad \hat{a}_{\boldsymbol{k}}|0\rangle \;=\; 0$$

obtaining

$$X_k'' + \omega_k^2 X_k \;=\; 0\,, \quad \text{with} \quad \omega_k^2 \;=\; k^2 + a^2 m_{\rm eff}^2$$

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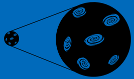
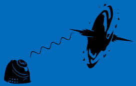
obtaining

$$X_k'' + \omega_k^2 X_k \;=\; 0\,, \quad \text{with} \quad \omega_k^2 \;=\; k^2 + a^2 m_{\rm eff}^2$$

For a mode inside the horizon,

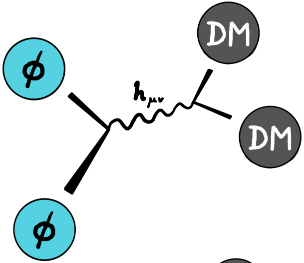
$$\omega_k^2 \;=\; \underbrace{k^2}_{\text{free particle}} + \mathcal{O}\left(\underbrace{\frac{a^2H^2}{k^2}}_{\text{interactions}}\right) \;>\; 0$$

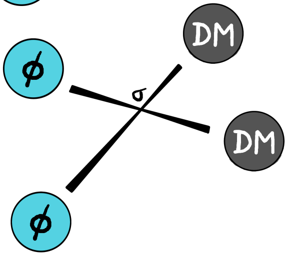




Perturbative DM production

The perturbative picture: inflaton, gravity and dark matter as (quasi)particles





1. Build the free particle and condensate states

$$|\mathrm{DM}; \boldsymbol{P}\rangle\,, \qquad |\phi\rangle$$

2. Linearize the interactions

$$\mathcal{L}_I \;=\; -\frac{1}{M_P} h_{\mu\nu}\left(T^{\mu\nu}_{\phi} + T^{\mu\nu}_{\chi}\right) - \frac{\sigma}{2}\phi^2\chi^2$$

3. Compute the annihilation amplitude

$$|\langle \mathrm{DM}; \boldsymbol{P}, \boldsymbol{P}'|\exp\left(i\int d^4x\,\mathcal{L}_I\right)|\phi\rangle|^2 \;\propto\; |\mathcal{M}|^2$$

4. Solve the Boltzmann equation

$$\frac{\partial f_\chi}{\partial t} - H|\boldsymbol{P}|\frac{\partial f_\chi}{\partial|\boldsymbol{P}|} \;=\; \frac{\pi|\mathcal{M}|^2}{2m_\phi^2}\delta(|\boldsymbol{P}| - m_\phi)$$

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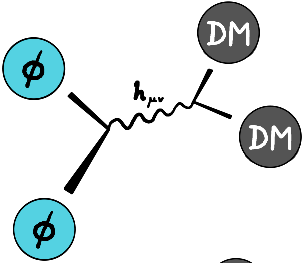

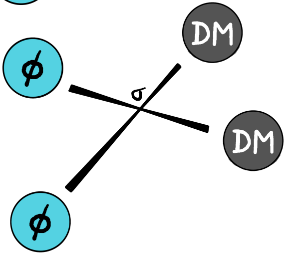

The amplitude is

$$|\mathcal{M}|^2 \;=\; \frac{1}{8}\frac{\rho_\phi^2}{m_\phi^4}\hat{\sigma}^2$$

where

$$\hat{\sigma} \;\equiv\; \sigma - \lambda(1-6\xi)$$

The Phase Space Distribution is

$$f_\chi(q,t) \;=\; \frac{\sqrt{3}\pi\hat{\sigma}^2\rho_{\rm end}^{3/2}M_P}{16m_\phi^7}\left(\frac{H_{\rm end}}{m_\phi}\,q\right)^{-9/2}\theta(q-1) \times \theta\left(\frac{a(t)}{a_{\rm end}} - \frac{H_{\rm end}}{m_\phi}\,q\right)$$

with $\quad q \equiv \frac{|\boldsymbol{P}|}{T_\star}\left(\frac{a}{a_{\rm end}}\right)\,, \quad T_\star \equiv H_{\rm end}$

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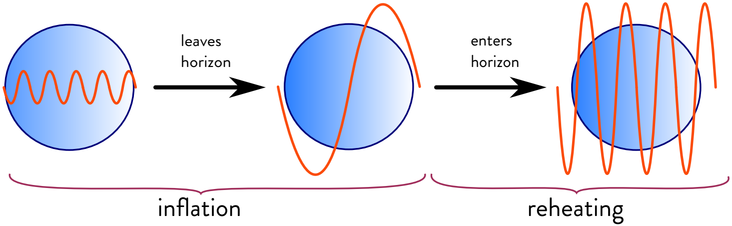
Gravitational particle production during inflation

Light scalar fields are unstable during inflation

$$X_k'' + \omega_k^2 X_k = 0\,, \quad \text{with} \quad \omega_k^2 = k^2 + 2(aH)^2 \left[\frac{m_\chi^2}{2H^2} + \frac{\sigma\phi^2}{2H^2} - 1 + 6\xi\right]$$

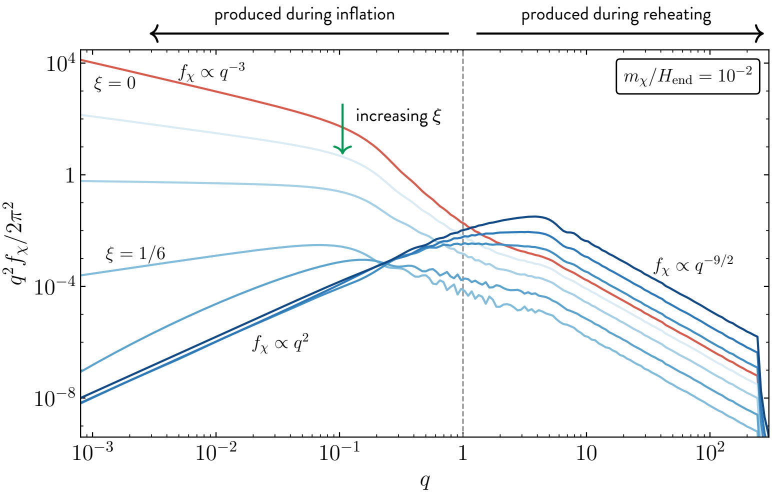
For a mode that is outside the horizon ($k/aH \ll 1$),

$$\omega_k^2 < 0 \quad \text{if} \quad m_\chi^2 < 2H^2\,,\ \sigma/\lambda \ll 1, \quad \text{and} \quad \xi < 1/6 \qquad \text{(tachyonic instability)}$$



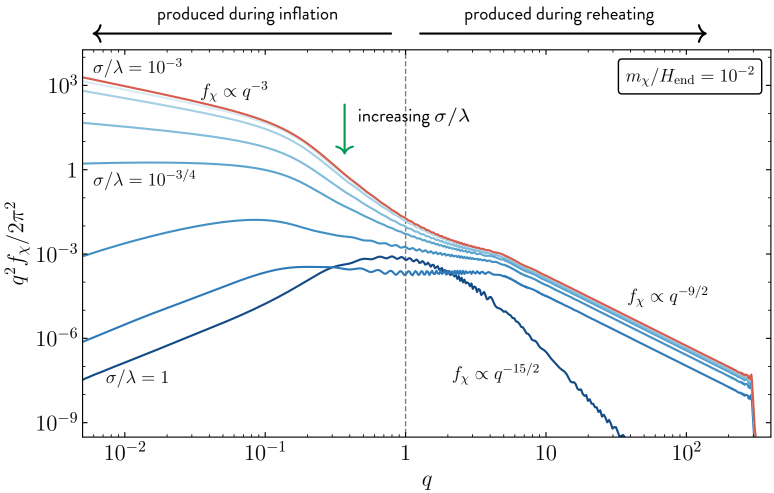
No free particle state during inflation $\Rightarrow$ no perturbative picture

Gravitational production



$$f_\chi \propto q^{-2\nu}\,, \quad \nu = \sqrt{9/4 - 12\xi - m_\chi^2/H^2}$$

Weak inflaton coupling



Inexact interference for $\sigma/\lambda = 1$

Strong inflaton coupling

Linear regime: The inflaton remains a condensate $\Rightarrow$ Hartree aproximation

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi + \sigma\langle\chi^2\rangle\phi \;=\; 0$$

$$\langle\chi^2\rangle \;=\; \frac{1}{(2\pi)^3 a^2}\int d^3\mathbf{p}\,\left(|X_p|^2 - \frac{1}{2\omega_p}\right)$$

L. Kofman, A. Linde, A. Starobinsky, PRD 56 (1997) 3258

MG, K. Kaneta, Y. Mambrini, K. Olive, S. Verner, JCAP 03 (2022) 016

Non-linear regime: The inflaton is fragmented $\Rightarrow$ ($\mathcal{C}$osmo)$\mathcal{L}$attice

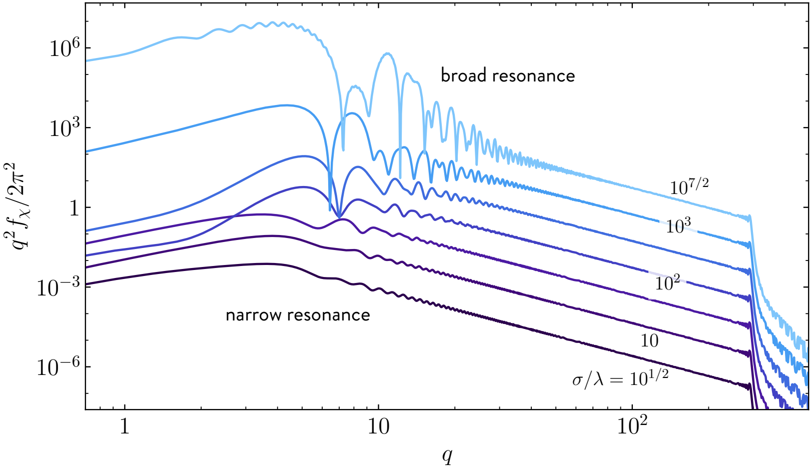
$$\ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2\phi}{a^2} + V_{,\phi} \;=\; 0$$

$$\ddot{\chi} + 3H\dot{\chi} - \frac{\nabla^2\chi}{a^2} + V_{,\chi} \;=\; 0$$

D. Figueroa, et al., Comput. Phys. Commun. 283, 108586 (2023)

Linear regime

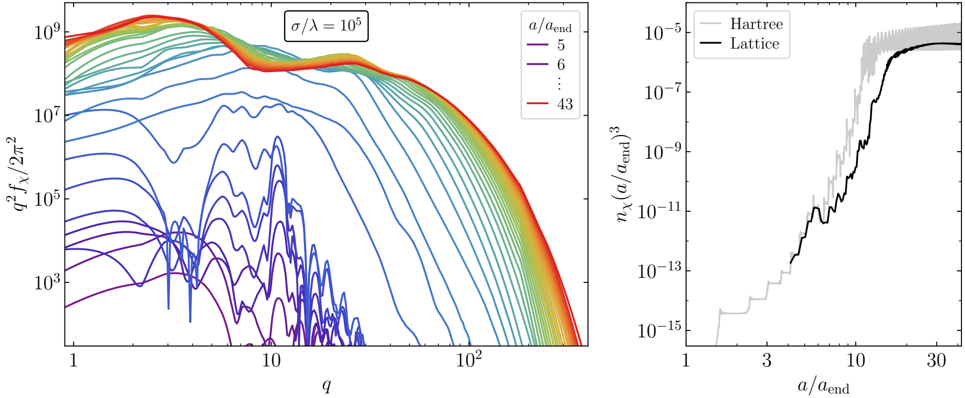
Appearance of parametric resonance, $f_\chi(p) \sim e^{2\mu_p m_\phi t}$

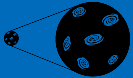


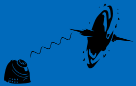
Non-linear regime

Re-scattering leads to a broader distribution with pseudo-thermal tail for ϕ and χ

$$f_\chi \sim e^{-\alpha(\sigma/\lambda;t)\,q} \quad \text{in the UV}$$

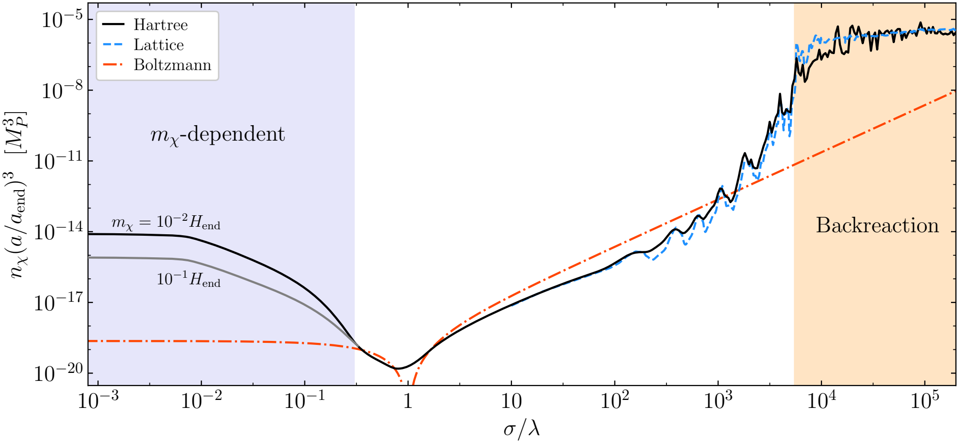






Number densities

The Boltzmann approximation has a *very limited* range of validity



Relic abundance, gravitational production

If $m_\chi \ll H_{\rm end}$ and $\xi \ll 1$,

$$\Omega_{\rm DM} \simeq \frac{\rho_\chi}{\rho_c}$$

$$\propto \frac{m_\chi T_{\rm reh}}{M_P^2} \underbrace{\int dq\, q^2 f_\chi(q)}_{\propto\, m_\chi^{-1}}$$

20 GeV

m_χ :

Relic abundance, gravitational production

If $m_\chi \ll H_{\rm end}$ and $\xi \gtrsim 1/6$,

$$\Omega_{\rm DM} \simeq \frac{\rho_\chi}{\rho_c}$$

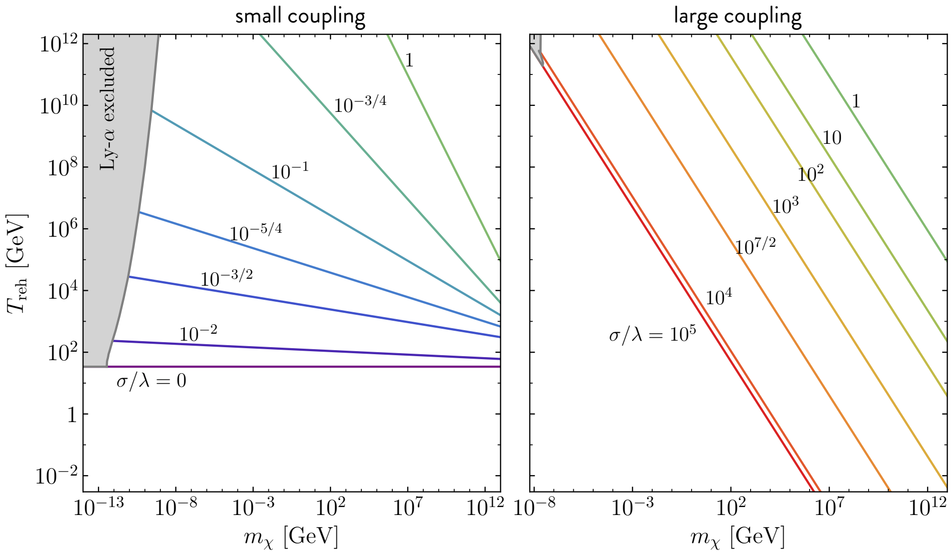
$$\propto \frac{m_\chi T_{\rm reh}}{M_P^2} \underbrace{\int dq\, q^2 f_\chi(q)}_{F(\xi)}$$

$\downarrow$

increasing m_χ

m_χ :

Relic abundance, inflaton decay



Isocurvature

Adiabatic perturbations: a single dynamical variable fixes the inhomogeneities

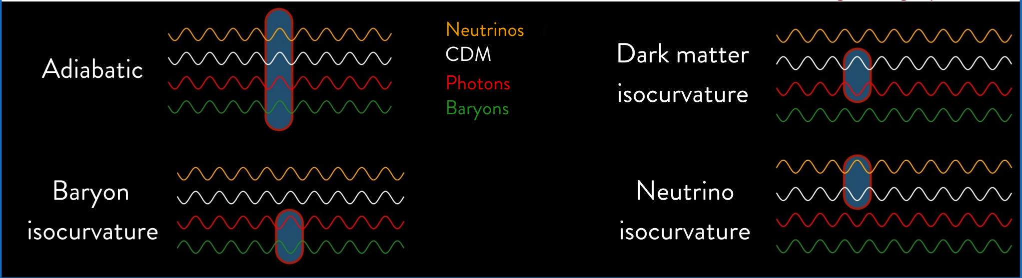
$$\delta\phi(\mathbf{x}, t) \xrightarrow{\mathcal{R}} \delta\rho_\gamma(\mathbf{x}, t)$$

$$\delta\phi(\mathbf{x}, t) \xrightarrow{\mathcal{R}} \delta\rho_{\mathrm{DM}}(\mathbf{x}, t)$$

The relative entropy is

$$\mathcal{S}_{\mathrm{DM},\gamma} = -3H\left(\frac{\delta\rho_\gamma}{\dot\rho_\gamma} - \frac{\delta\rho_{\mathrm{DM}}}{\dot\rho_{\mathrm{DM}}}\right) = 0$$

Original image by Dan Grin



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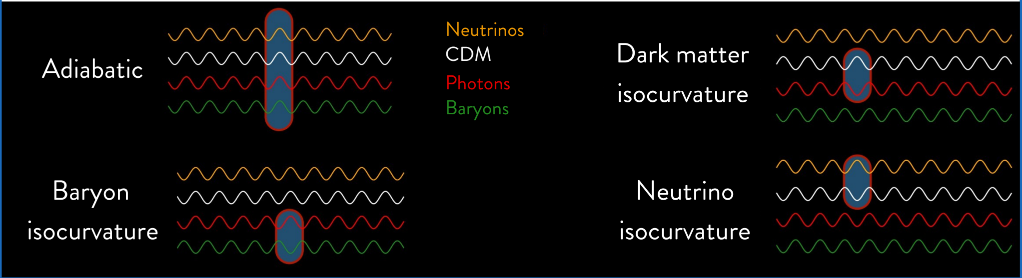
Isocurvature

Isocurvature perturbations: several dynamical variables fix the inhomogeneities

$$\delta\phi(\mathbf{x},t) \xrightarrow{\mathcal{R}} \delta\rho_\gamma(\mathbf{x},t)$$
$$\delta\chi(\mathbf{x},t) \xrightarrow{\mathcal{S}} \delta\rho_{\rm DM}(\mathbf{x},t)$$

The relative entropy is

$$\mathcal{S}_{{\rm DM},\gamma} = -3H\left(\frac{\delta\rho_\gamma}{\dot\rho_\gamma} - \frac{\delta\rho_{\rm DM}}{\dot\rho_{\rm DM}}\right) \neq 0$$



Isocurvature in the CMB

Isocurvatures would leave an imprint in the CMB

CDI: cold dark matter density isocurvature

NDI: neutrino density isocurvature

NVI: neutrino velocity isocurvature

However, they have not been detected,

$$\beta_{\rm iso} = \frac{\mathcal{P}_\mathcal{S}}{\mathcal{P}_\mathcal{R} + \mathcal{P}_\mathcal{S}} < \begin{cases} 2.5\% \text{ (CDI)} \\ 7.4\% \text{ (NDI)} \\ 6.8\% \text{ (NVI)} \end{cases}$$

This constraint applies only at large scales ($k_* = 0.002\,\mathrm{Mpc}^{-1}$)

At smaller scales, ¯_(ツ)_/¯

Y. Akrami et al. [Planck], Astron. Astrophys. 641, A10 (2020)

1. Dark Matter

2. Inflation

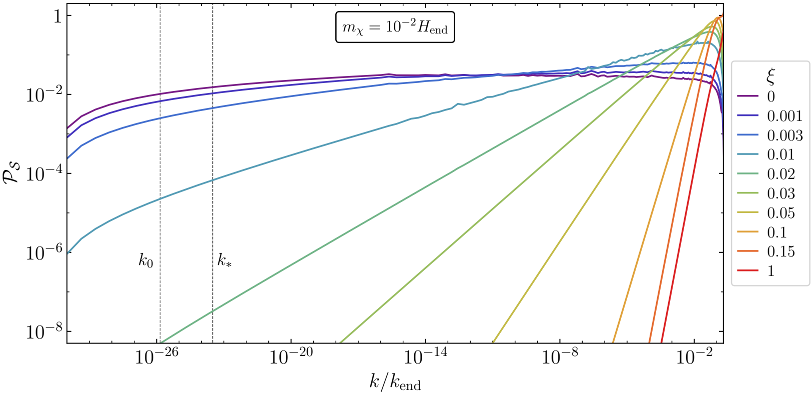
3. Production

4. Limits

5. Prospects

Isocurvature in gravitational production

The growth of χ fluctuations during inflation sources isocurvature

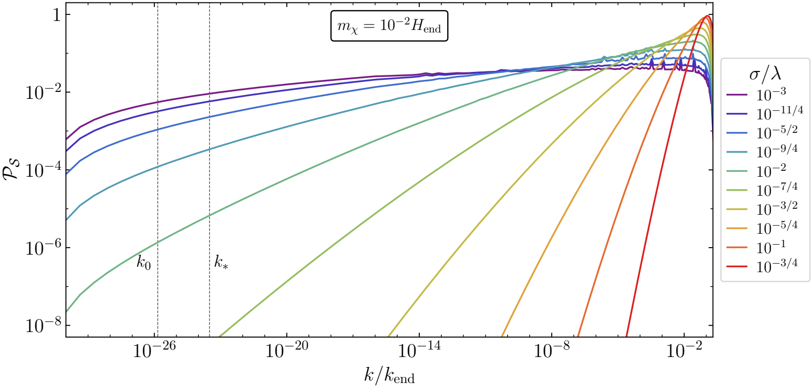


$$\mathcal{P}_S(k) = \frac{k^3}{2\pi^2 \rho_\chi^2} \int d^3\mathbf{x} \, \langle \delta\rho_\chi(\mathbf{x}) \delta_\chi(0) \rangle \, e^{-i\mathbf{k}\cdot\mathbf{x}} \quad \Rightarrow \quad \begin{aligned} m_\chi &\gtrsim 0.54\, H_{\rm inf} \\ \xi &\gtrsim 0.03 \end{aligned}$$

D. Chung, E. Kolb, A. Riotto, L. Senatore, PRD 72, 023511 (2005)

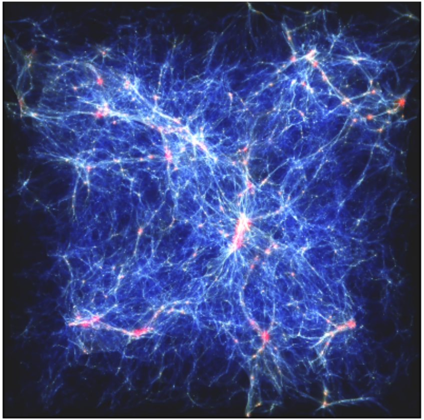
Isocurvature in production from inflaton decay

The growth of χ fluctuations during inflation sources isocurvature

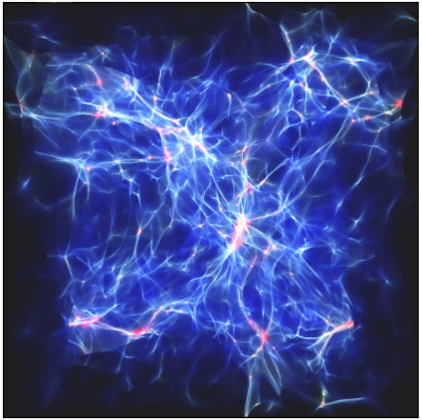


$$\mathcal{P}_S(k) = \frac{k^3}{2\pi^2 \rho_\chi^2} \int d^3\mathbf{x}\, \langle \delta\rho_\chi(\mathbf{x}) \delta_\chi(0) \rangle\, e^{-i\mathbf{k}\cdot\mathbf{x}} \quad \Rightarrow \quad \begin{array}{l} m_\chi \gtrsim 0.54\, H_{\rm inf} \\ \sigma/\lambda \gtrsim 0.02 \end{array}$$

Non-Cold Dark Matter and structure formation



CDM

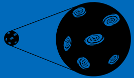


WDM (0.5 keV)

J. Baur et al., JCAP 08 (2016), 012

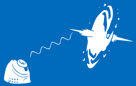
1. Dark Matter

2. Inflation



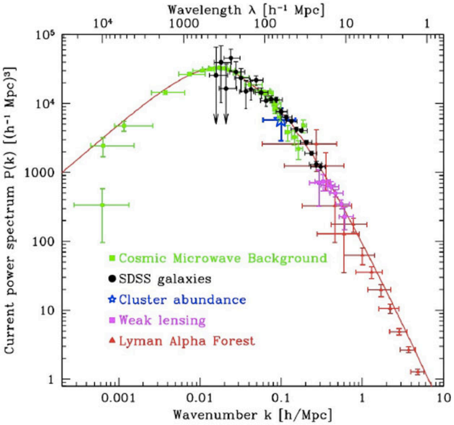
3. Production

4. Limits

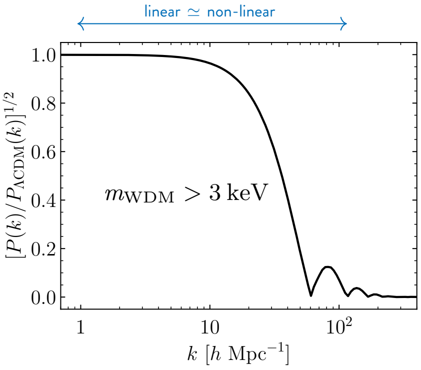


5. Prospects

How warm are non-thermal relics?



R. Murgia, V. Iršič and M. Viel, PRD 98 (2018), 083540



G. Ballesteros, MG and M. Pierre, JCAP 03 (2021), 101

1. Dark Matter

2. Inflation

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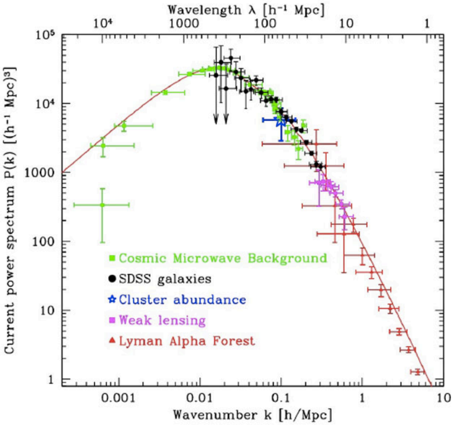
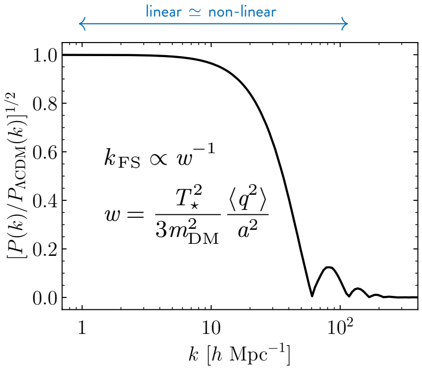
4. Limits

5. Prospects

How warm are non-thermal relics?

R. Murgia, V. Iršič and M. Viel, PRD 98 (2018), 083540





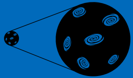
G. Ballesteros, MG and M. Pierre, JCAP 03 (2021), 101

$$w(m_{\mathrm{DM}}) = w_{\mathrm{WDM}}(m_{\mathrm{WDM}}) \longrightarrow$$

$$\boxed{m_{\mathrm{DM}} = m_{\mathrm{WDM}}\left(\frac{T_\star}{T_{\mathrm{WDM}}}\right)\sqrt{\frac{\langle q^2\rangle}{\langle q^2\rangle_{\mathrm{WDM}}}}}$$

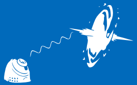
1. Dark Matter

2. Inflation



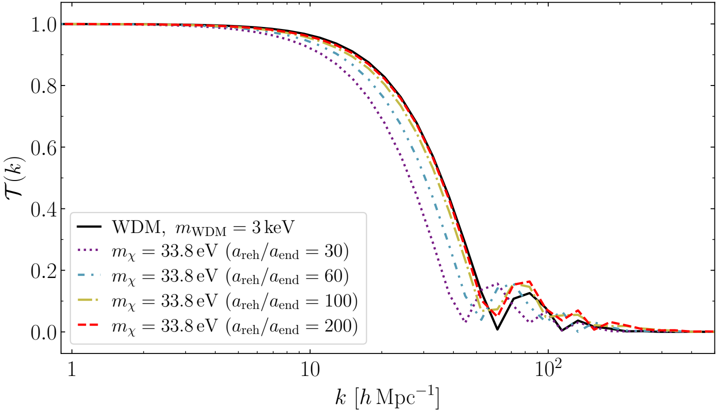
3. Production

4. Limits



5. Prospects

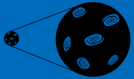
Light, but cold enough, dark matter



$$\langle q^2 \rangle \propto \begin{cases} (a_{\rm reh}/a_{\rm end})^{1/2}\,, & \xi \gtrsim 1/4 \\ m_\chi^\alpha\,, & \xi \lesssim 1/4 \end{cases} \quad \Rightarrow \quad m_\chi \gtrsim \begin{cases} 33\,\mathrm{eV}\,, & \xi \gtrsim 1/4 \\ 0.2\,\mathrm{meV}\,, & \xi \lesssim 1/4 \end{cases}$$

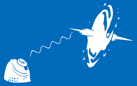
1. Dark Matter

2. Inflation



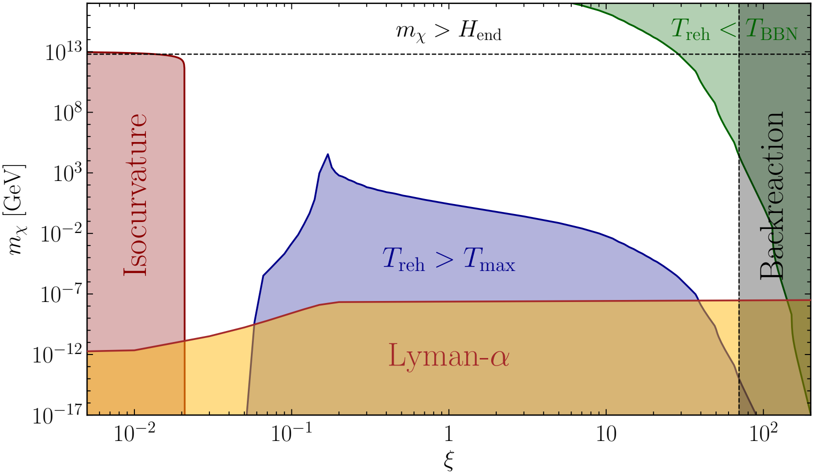
3. Production

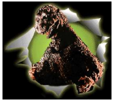
4. Limits



5. Prospects

Parameter space for gravitational production

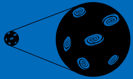




WIMPZILLAS

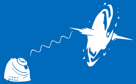
1. Dark Matter

2. Inflation



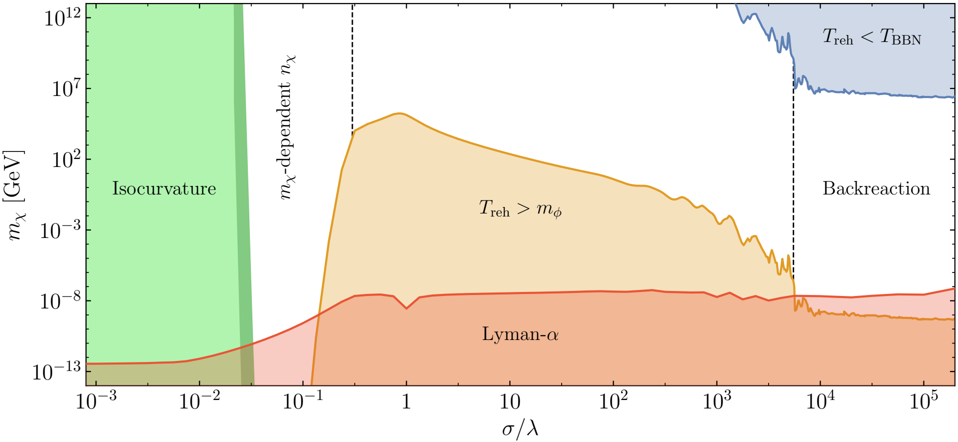
3. Production

4. Limits



5. Prospects

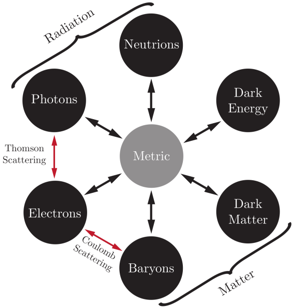
Parameter space for production from inflaton decay



Additional constraints?

Distortions of the CMB frequency spectrum

$$f(E) = \frac{1}{e^{(E-\mu)/T} - 1}$$



Energy injected into the CMB at different times results in a spectrum that mixes regions at different temperatures

FIRAS: $|\mu| < 9 \times 10^{-5}$

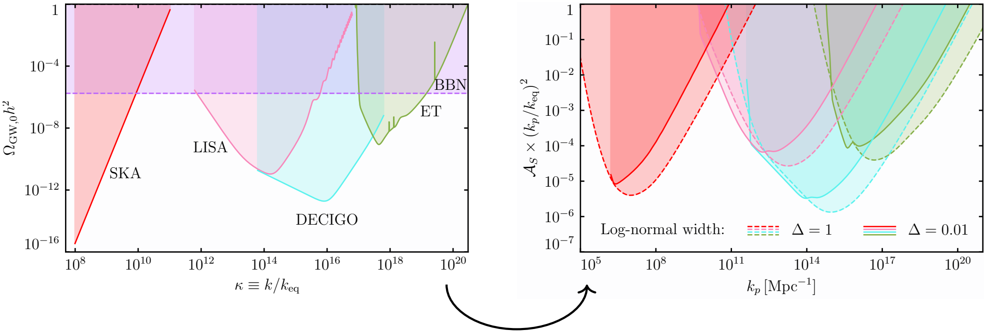
PIXIE: $|\mu| < 10^{-9}$

D. Fixsen et al., Astrophys. J. 473 (1996), 576

Additional constraints?

Isocurvature-induced gravitational waves

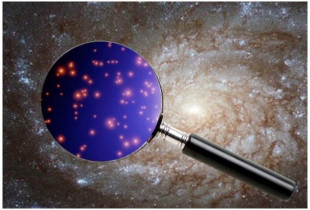
G. Domènech, S. Passaglia and S. Renaux-Petel, JCAP 03 (2022), 023



$$h''_{ij} + 2\mathcal{H}h'_{ij} + \nabla^2 h_{ij} = \frac{2}{M_P^2}\left[\partial_i\phi\partial_j\phi\right]^{\mathrm{TT}}$$

$$\Omega_{\mathrm{GW,c}}(k) = \frac{2}{3}\int_0^\infty dv \int_{|1-v|}^{1+v} du \left(\frac{4v^2-(1-u^2+v^2)^2}{4uv}\right)^2 \overline{I^2(x_c, k, u, v)}\mathcal{P}_S(ku)\mathcal{P}_S(kv)$$

Additional constraints?

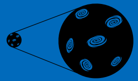


Blue tilted isocurvature: Ultra Compact Mini Halos

M. Ricotti and A. Gould, Astrophys. J. 707 (2009), 979; T. Bringmann et al., PRD 85 (2012), 125027

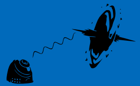
1. Dark Matter

2. Inflation



3. Production

4. Limits

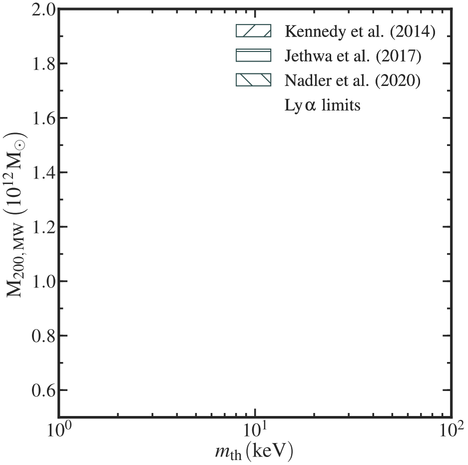


5. Prospects

Structure formation

Limits in the “warmness” of dark matter using the satelite galaxies of the Milky Way

Mass of the Milky Way’s DM halo

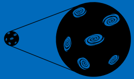


GALFORM model of galactic formation ($z_{\mathrm{reion}} = 7$)

O. Newton et al., JCAP 08 (2021), 062

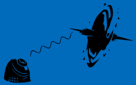
1. Dark Matter

2. Inflation



3. Production

4. Limits



5. Prospects

Thank you