arXiv:2603.22394

Kinetic Isocurvature Perturbation

A New Class of Primordial Fluctuations in Dark Matter

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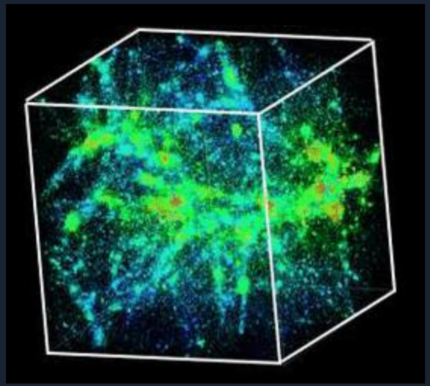
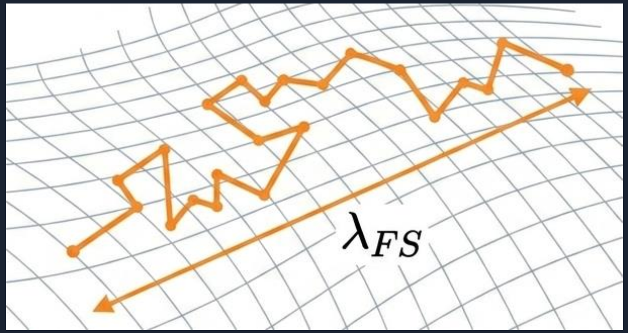
A question for the next generation of surveys

As small-scale observations improve — Lyman-α forests, strong lensing, galaxy surveys — we will measure quantities like the dark matter free-streaming scale λ_{FS} ($< O(\text{Mpc})$) with increasing precision.

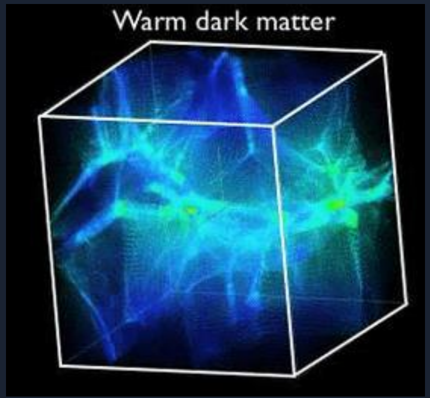
Could λ_{FS} measured in one patch of the sky differ from λ_{FS} in a distant patch?

Is there a large-scale spatial modulation of small-scale structure?





$$\lambda_{FS} = \int_0^{t_{eq}} dt \, \frac{v(t)}{a(t)}$$



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NAIVE EXPECTATION

Large-scale (≫ Mpc) density perturbations are tiny: $\delta\rho/\rho \sim 10^{-5}$. In the standard picture, distant patches are not expected to carry systematically different free-streaming cutoffs.

But is this really the only possibility? Can we find a mechanism that allows O(1) differences?

The barrier — and the way around it

THE BARRIER

For λ_{FS} to differ across patches, one might think that a standard large-scale iso. perturbation must exist. But standard DM isocurvature

$$\delta\left(\frac{\rho_{DM}}{s}\right)$$

is constrained by CMB to sub-sub-percent — forbidding significant variation.

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THE BREAKTHROUGH

What if the perturbation lives in DM kinetic energy, not number density?

As DM cools, $\delta\rho_{DM}$ from kinetic energy redshifts away — the usual CMB isocurvature bound is naturally avoided. But λ_{FS} modulation survives, allowing $O(1)$ patch-to-patch differences.

This opens the door to a new class of observables — the long-range correlation of the small-scale power spectrum.

The paradigm shift: kinetic isocurvature perturbations

Instead of fluctuating particle number, let the momentum distribution vary from patch to patch.

The mass density stays constant — only the kinetic energy fluctuates.

STANDARD ISOCURVATURE

Patches A and B have different numbers of DM particles.

$$\delta n_{DM} \neq 0$$

→ **Highly constrained by Planck CMB**

KINETIC ISOCURVATURE · THIS WORK

Patches A and B have the same number but different momenta.

$$\delta n_{DM} = 0, \ \delta p_{DM} \neq 0$$

→ **Usual CMB bounds naturally avoided**

A distinct isocurvature mode can be sourced by how DM moves at production, not by how much DM is produced.

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Anatomy of the energy-density perturbation

The perturbation of the DM energy density $\rho_{DM} = E_{DM} n_{DM}$ $\left(E_{DM} = \sqrt{m_{DM}^2 + p_{DM}^2}\right)$ decomposes into two independent terms.

$$\frac{\delta\rho_{DM}}{\rho_{DM}} = \frac{\delta n_{DM}}{n_{DM}} + \frac{p_{DM}^2}{E_{DM}^2}\frac{\delta p_{DM}}{p_{DM}}$$

STANDARD TERM

Fluctuation in comoving number density. Set to zero in this framework (adiabatic).

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KINETIC TERM

Weighted by p^2/E^2. Dominant when DM is relativistic; vanishes as DM cools.

***In warm-DM scenarios** this momentum term becomes cosmologically significant.*

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A simple realization (modulated decay)

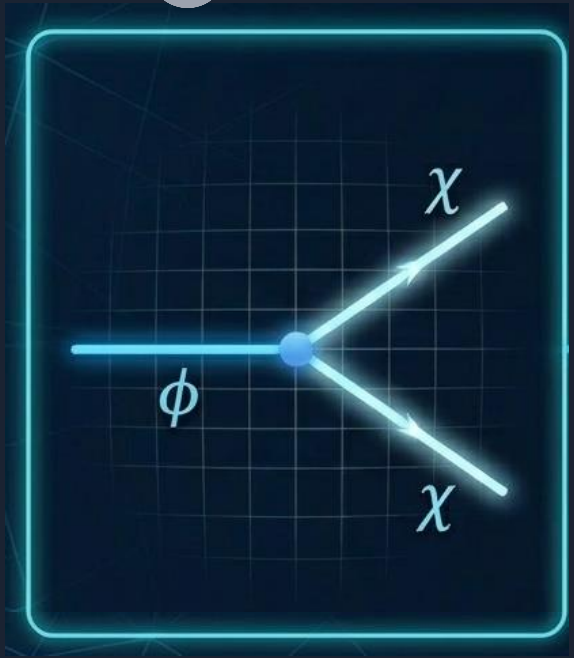
Exotic new observables often require exotic models — but not here. A subdominant scalar ϕ decays into light DM χ through a coupling modulated by a field σ. This minimal setup naturally delivers $\delta n_\chi = 0$ with $\delta p_\chi \neq 0$.

1 Source

$\mathcal{L} = A\phi\chi^2$
(χ: boson)

$\mathcal{L} = y\phi\bar{\chi}\chi$
(χ: fermion)

$$\mathcal{L} = \frac{(\phi\chi)(\chi\chi)}{\Lambda^2}$$
(ϕ: fermion)



Heavy scalar ϕ
(subdominant, nonrelativistic)

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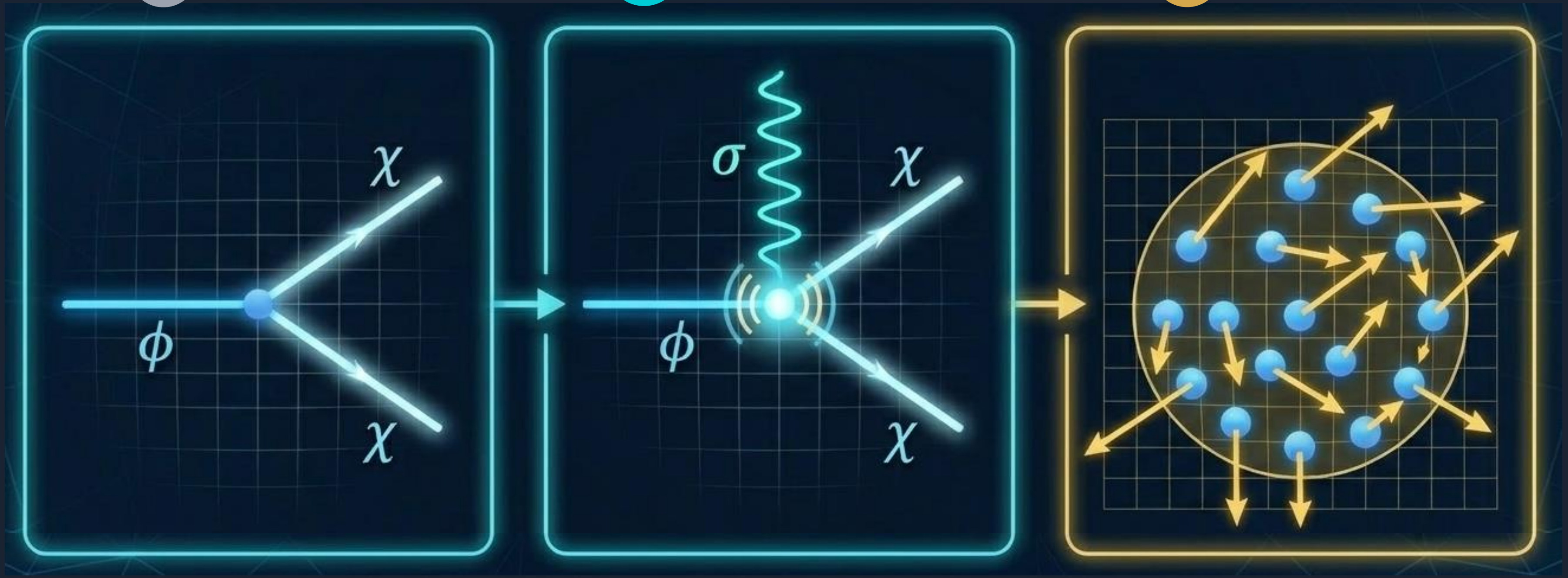
2 Modulator

3 Product



Heavy scalar ϕ
(subdominant, nonrelativistic)

Field σ with $\delta\sigma$ modulates the coupling constant so that

$$\Gamma \to \Gamma + \delta\Gamma$$

χ produced relativistic with patch-dependent momentum.

$\delta n_\chi = 0, \qquad \delta p_\chi \neq 0$

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Does the modulator close consistently?

The modulating field σ sets the decay rate. A few mild conditions keep the whole construction cosmologically safe.

$$\mathcal{L}_{\rm int} = g\sigma\phi\chi^2, \qquad \Gamma_\phi \simeq \frac{1}{8\pi}\frac{g^2\sigma_i^2}{m_\phi}$$

KEEPING THE MODULATION ALIVE

σ must stay frozen until after ϕ decays:

$$m_\sigma < \frac{T_{dec}^2}{M_P} \simeq 1\ \text{GeV}\left(\frac{T_{dec}}{10^9\ \text{GeV}}\right)^2$$

which bounds the coupling (safe from loop-induced ϕ dependent contributions):

$$g < \ 10^{-8}\left(\frac{T_{NR}}{10\ \text{keV}}\right)^{1/2}\left(\frac{m_\phi}{10^8\ \text{GeV}}\right)$$

NOT SPOILING OTHER OBSERVABLES

Curvaton perturbation from σ stays sub-dominant:

$$\mathcal{R}_\sigma \sim \frac{\delta\sigma}{\sigma_i}\frac{\sigma_i^2}{M_P^2}\frac{\sqrt{m_\sigma M_P}}{T_{dis}} \ll \mathcal{R}_{\rm obs}$$

and σ must be heavy enough to avoid extra $\Delta N_{\rm eff}$:

$$m_\sigma \gg\ \text{MeV} \quad \Rightarrow \quad T_{dec}\ >\ 10^8\ \text{GeV}$$

All four conditions are satisfied in a viable parameter range.

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The redshift mechanism and effects on small scales

$T(a_i) \gg \text{keV}$

STAGE 1 — RELATIVISTIC

$$p_i = p_\chi(a_i) \simeq \frac{m_\phi}{2} \gg m_\chi$$

a_i is determined by Γ (ϕ decay rate)

$$1\phi \to 2\chi \;\Rightarrow\; N_\chi = 2N_\phi$$

$T(a_*) \sim \text{keV}$

STAGE 2 — EXPANSION/WARM

$$p_\chi(a_*) = p_i \frac{a_i}{a_*} \sim m_\chi$$

Momentum redshifts with the scale factor, and becomes warm

$T(a_f) \sim \text{eV}$

STAGE 3 — COLD

$$p_\chi(a_f) \ll m_\chi$$

When CMB scales enter , kinetic perturbation of DM is negligible

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While the energy-density contrast vanishes at late times, the momentum of DM around a_* dictates how far each DM particle travels — leaving a surviving spatial variation of the free-streaming scale

$$\frac{\delta\Gamma}{\Gamma} \Rightarrow \frac{\delta a_i}{a_i} \Rightarrow \frac{\delta p_\chi(a_*)}{p_\chi(a_*)} \Rightarrow \frac{\delta\lambda_{FS}}{\lambda_{FS}}, \qquad \frac{\delta\rho_\chi(a_f)}{\rho_\chi(a_f)} < 10^{-5}$$

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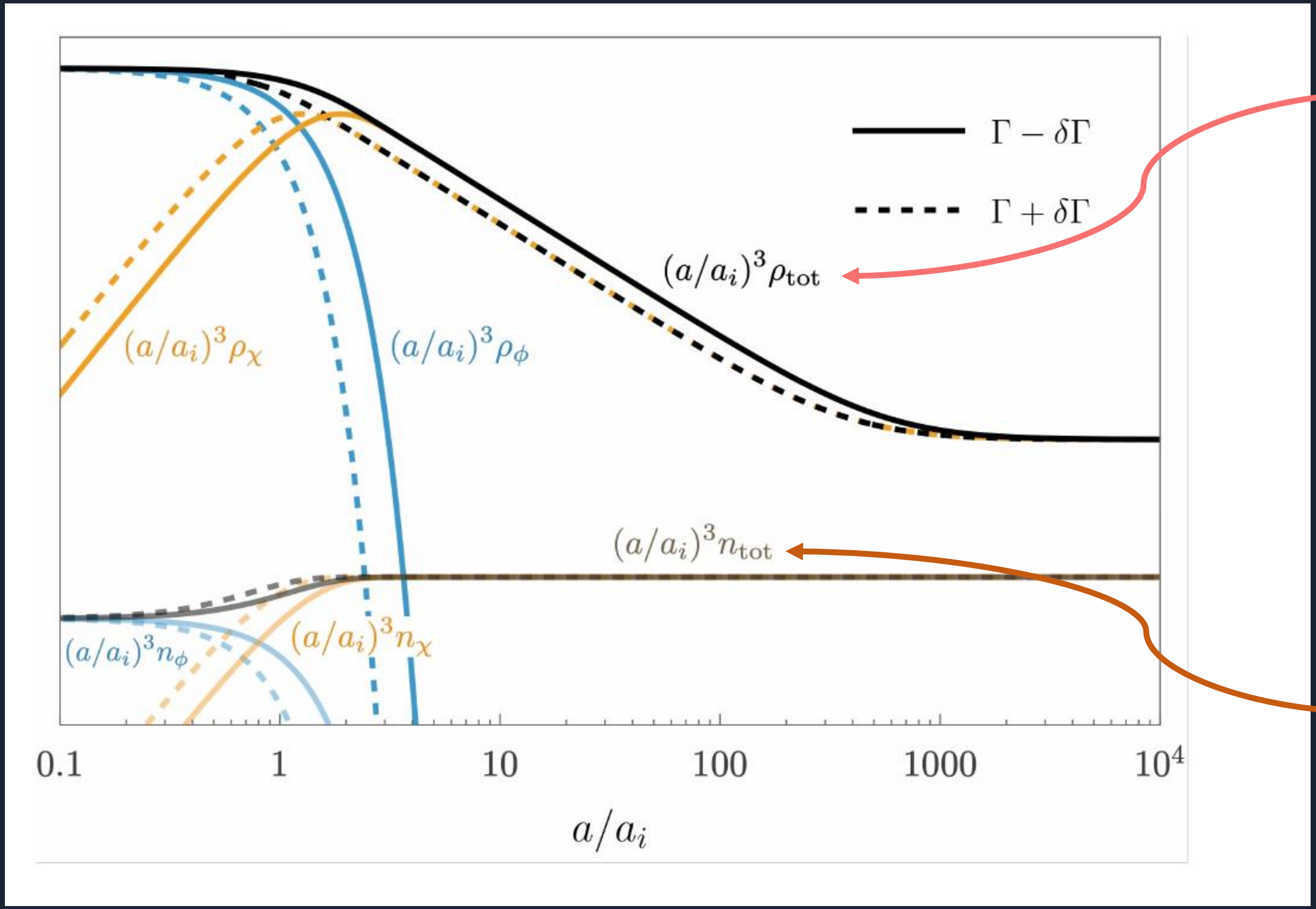
Comparisons

Model	δn_{DM}	δp_{DM}	$\delta \lambda_{FS}$	CMB safe?
Thermal WDM	Adiabatic	Adiabatic	0	Yes (no iso-perturbations)
Field-dependent WDM (e.g. axion)	$\neq 0$	$\neq 0$	$\neq 0$	No (strongly constrained)
Kinetic Isocurvature	$= 0$	$\neq 0$	$\neq 0$	**Yes**

Generous on CMB scales, sensitive on small scales — the fingerprint of kinetic isocurvature.

Cosmological evolution: Boltzmann equation analysis



Energy density fluctuates early on — $\delta\Gamma$ leaves a visible gap between curves.

The construction delivers what is needed: number density adiabatic, kinetic energy modulated.

Comoving number density after production converges adiabatically — independent of decay timing.

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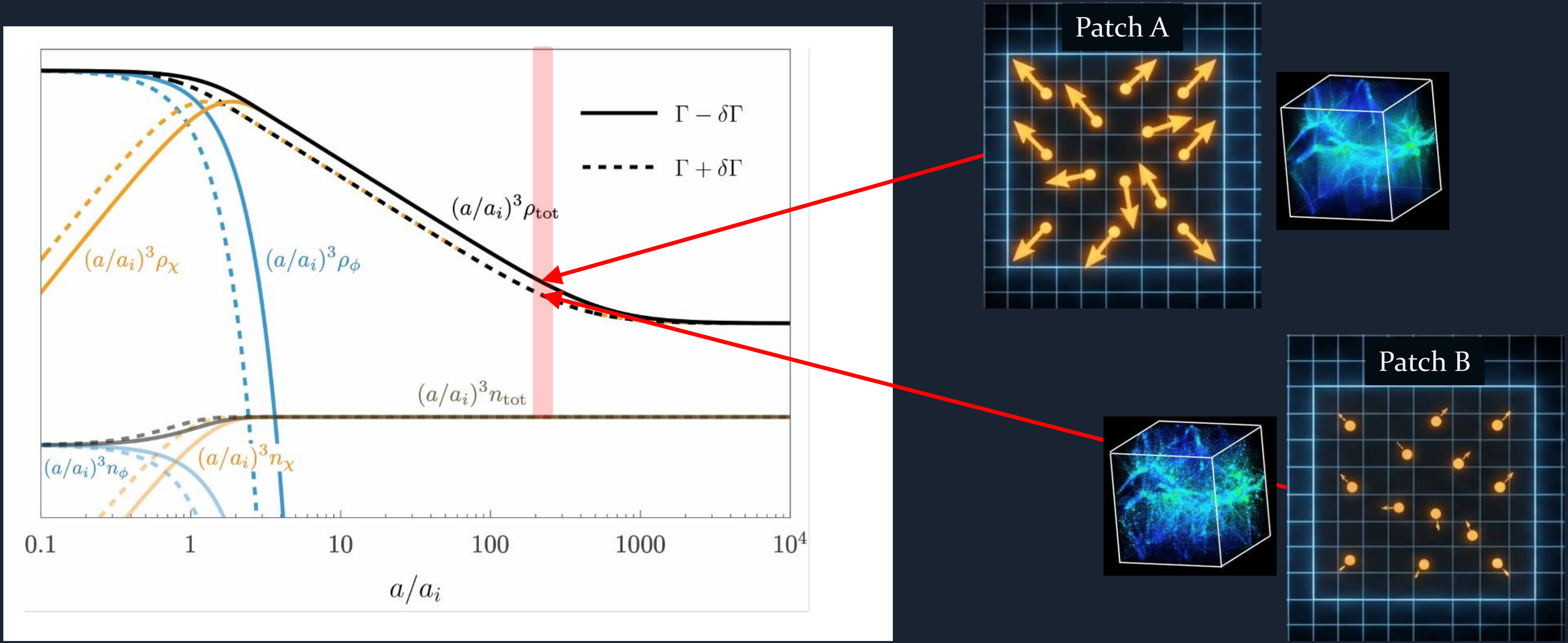
Small-scale suppression varies from patch to patch



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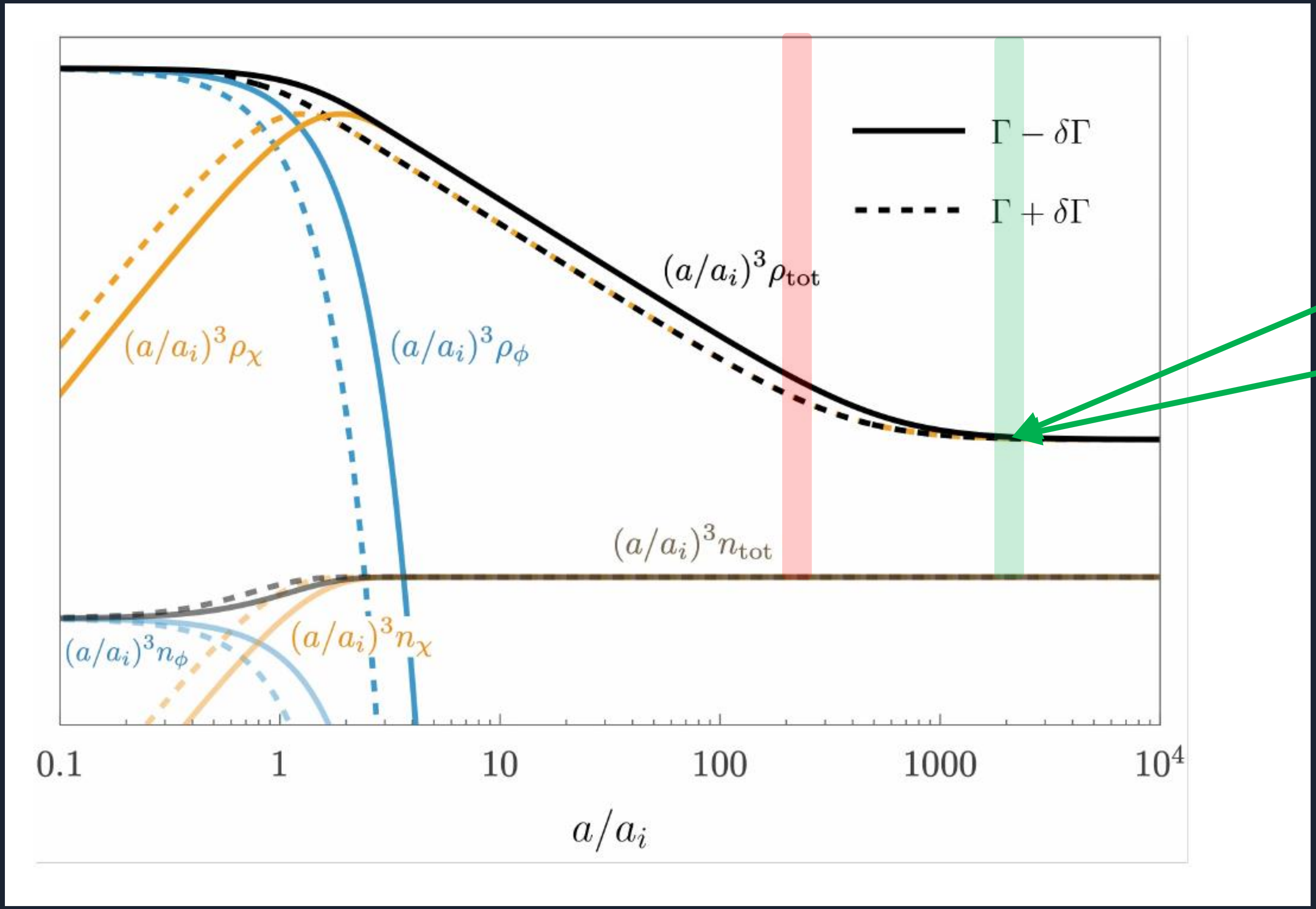
The density contrast fades on CMB scales



$\delta\Gamma$ initially produces a sizable $\delta\rho_\chi/\rho_\chi$. But as the universe expands, the kinetic weight $(a_i/a)^2$ shrinks. By the time CMB-scale modes enter the horizon, $\delta\rho_\chi/\rho_\chi$ is negligible.

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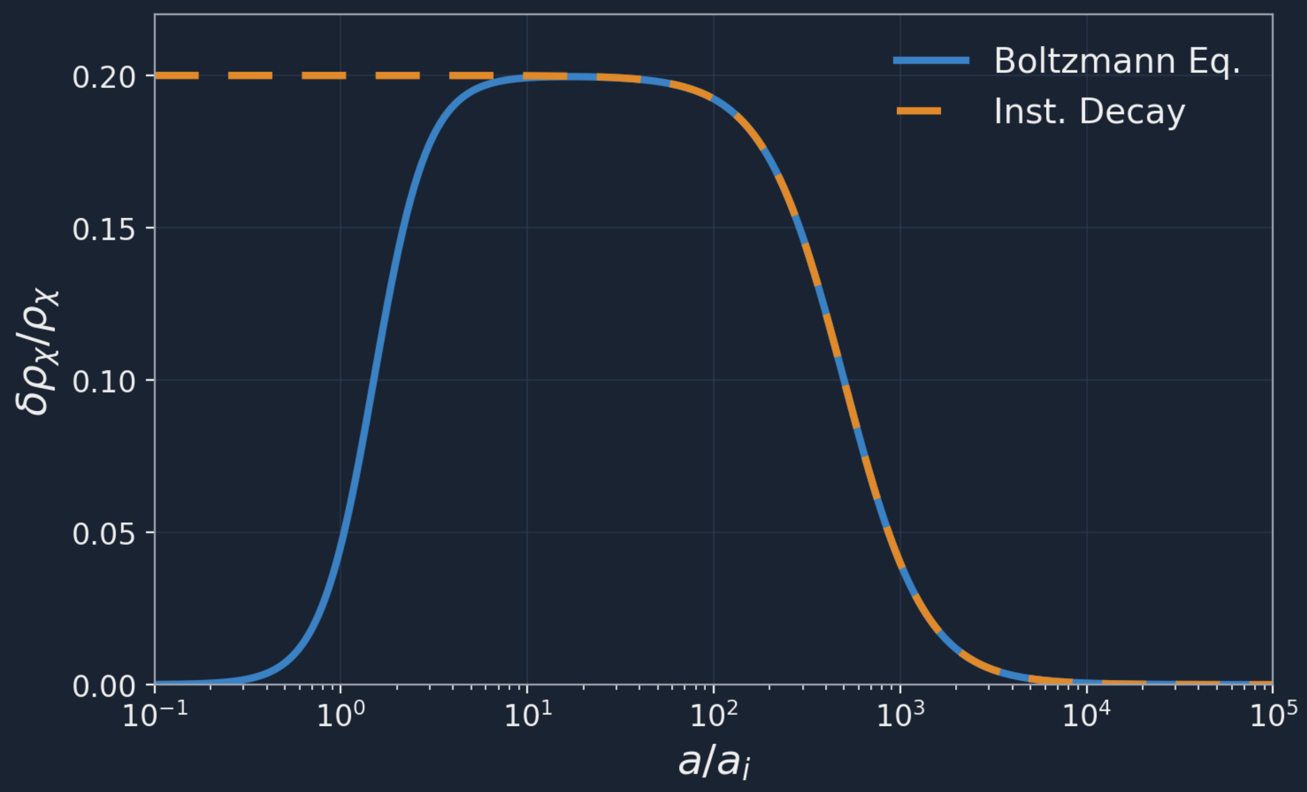
Analytic approximation



Boltzmann solution vs. instantaneous-decay approximation, ($m_\chi = 10^{-3} m_\phi, \delta\Gamma = 0.2\Gamma$).

The two curves overlap

Once production completes, the analytic result tracks the numerical solutions across the entire evolution.

Plateau then redshift

While χ is relativistic the contrast saturates near $\delta\Gamma/\Gamma$; as χ cools it redshifts toward zero.

This justifies the simple analytic relation used in the later constraint estimates.

$$\left(\frac{\delta\rho_\chi}{\rho_\chi}\right)_{\mathrm{inst}} \simeq -\frac{1}{2}\frac{\delta\Gamma}{\Gamma}\left(\frac{m_\phi^2 (a_i/a)^2}{4m_\chi^2 + m_\phi^2 (a_i/a)^2}\right)$$

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The surviving imprint

Kinetic energy history inscribed in the free-streaming scale

INITIAL STATE (fades)	CUMULATIVE INTEGRAL (transforms)	PERMANENT IMPRINT (preserved)
δp_{DM}	$\lambda_{FS} = \int \frac{dt}{a(t)} \frac{p_{DM}(a)}{E_{DM}(a)}$	$\frac{\delta\lambda_{FS}}{\lambda_{FS}}$
Large initial momentum fluctuation. Washed out by redshift.	Kinetic energy vanishes, but the comoving distance traveled is accumulated.	Spatial fluctuation of λ_{FS}. Permanently imprinted as the small-scale cutoff.

The kinetic energy is washed away by cosmic expansion —

but λ_{FS}, set by the initial dispersion, remains different from patch to patch.

The initial δp_{DM} is permanently transformed into $\delta\lambda_{FS}$.

Free-streaming length and Isocurvature perturbation

$$\lambda_{FS} \simeq 1\,\text{Mpc}\left(\frac{p_i^2}{m_\chi^2}\frac{t_i}{10^6\,\text{sec}}\right)^{1/2}\left[1 - 0.07\ln\left(\frac{p_i^2}{m_\chi^2}\frac{t_i}{10^6\,\text{sec}}\right)\right]$$

$$\delta_\lambda = \frac{\delta\lambda_{FS}}{\lambda_{FS}} = -\frac{1}{2}\frac{\delta\Gamma}{\Gamma}\left(1 + \frac{2\,K_\chi}{\ln\left((1+K_\chi)/(1-K_\chi)\right)}\right)$$

$$K_\chi = \frac{m_\chi}{\sqrt{m_\chi^2 + p_\chi^2(a_{eq})}} \simeq 1$$

$$\delta_\chi = \left(\frac{\delta\rho_\chi}{\rho_\chi}\right)_k \simeq \frac{\delta_\lambda}{1 + \frac{1.56}{\sqrt{g_*}}\left[1 + 0.27\ln\left(\frac{\text{Mpc}}{\lambda_{FS}}\right)\right]\left(\frac{\text{Mpc}}{\lambda_{FS}}\right)^2\left(\frac{6.7\,\text{Mpc}^{-1}}{k}\right)^2}$$

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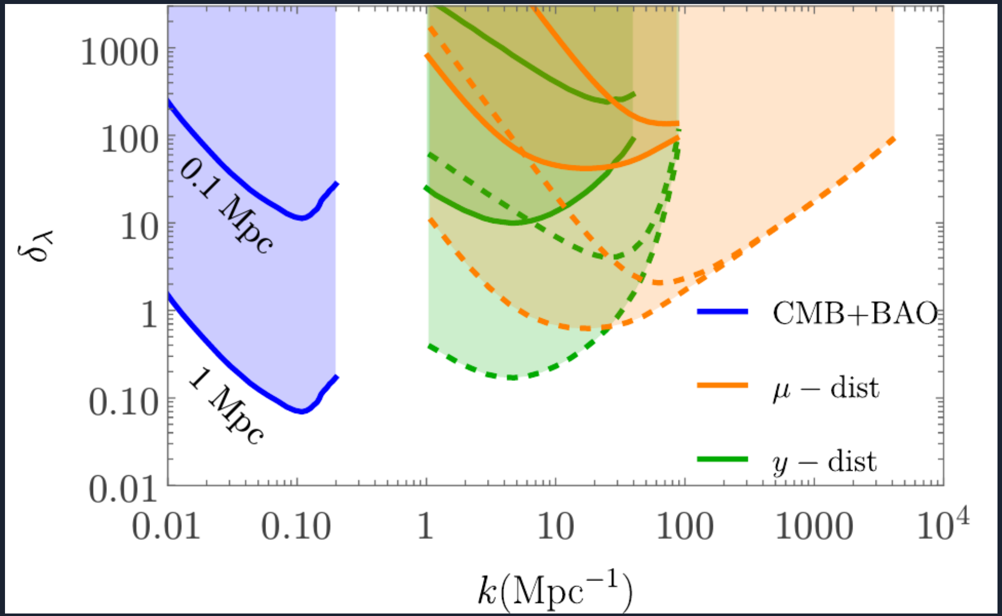
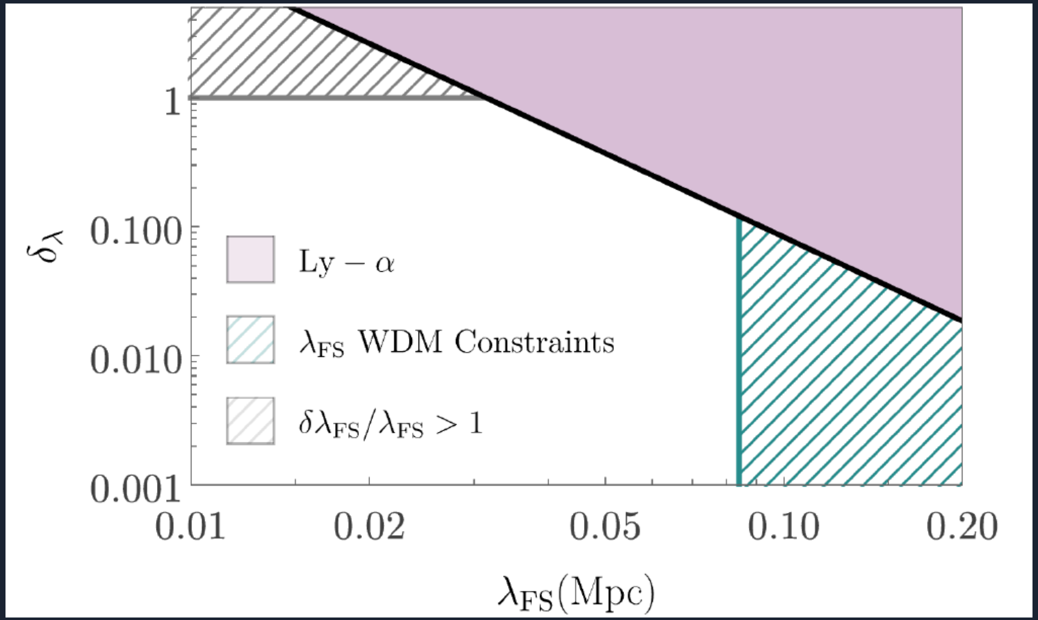
Isocurvature constraints from CMB+BAO and Lyman-α

$$P_{\delta_\lambda}^{(\text{delta})} = A_{\delta_\lambda}\delta(\ln(k/k_0))$$



Recasting neutrino density isocurvature (NDI) bounds (arXiv:2502.20434) gives conservative estimates. Low $k \longrightarrow$ CMB+BAO; high $k \longrightarrow$ spectral distortions.

$$P_{\delta_\lambda}^{(\text{flat})} = A_{\delta_\lambda}$$



For a flat δ_λ spectrum the dominant constraint comes from Lyman-α at $k \sim 1$ Mpc^{-1}. Still, $\delta_\lambda = O(0.1 - 1)$ survives over the warmness-allowed range.

$$P_{\delta_\chi}(k) \simeq g_*(0.1\,\lambda_{FS}k)^4 P_{\delta_\lambda}(k) \quad \text{for} \quad \lambda_{FS}k \ll 1\,, \qquad P_{\delta_\chi}(k) = P_{\delta_\lambda}(k) \quad \text{for} \quad \lambda_{FS}k > O(1)$$

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Isocurvature constraints from CMB+BAO and Lyman-α

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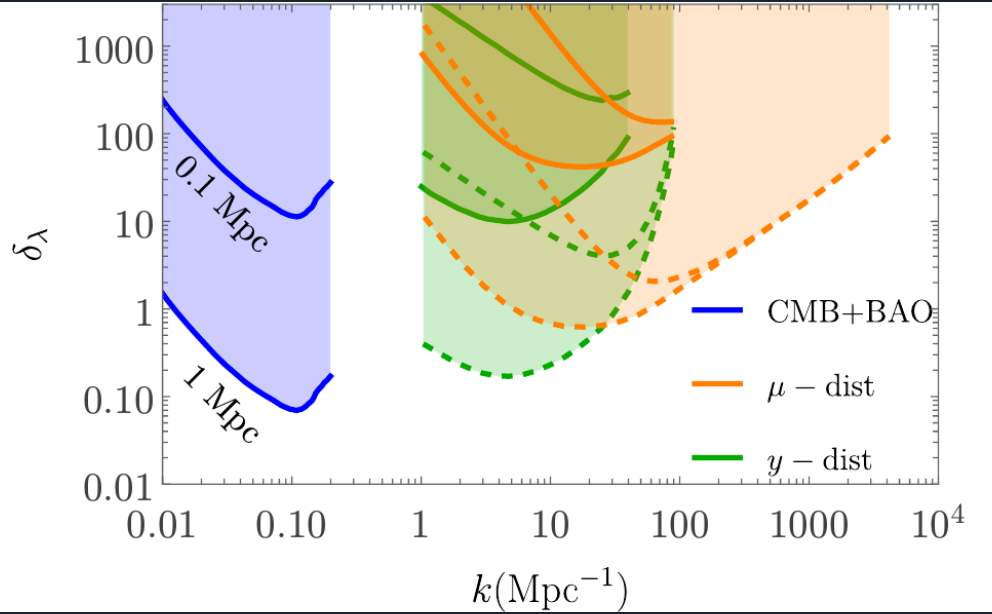

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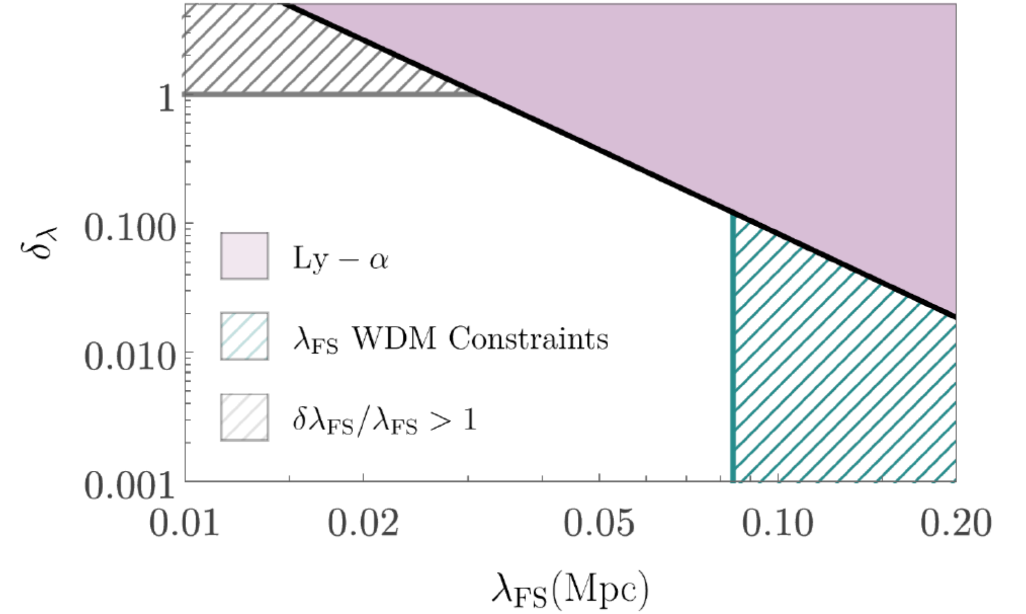

For a flat δ_λ spectrum the dominant constraint comes from Lyman-α at $k \sim 1$ Mpc^{-1}. Still, $\delta_\lambda = O(0.1\text{–}1)$ survives over the warmness-allowed range.

Bottom line:* $\boldsymbol{\delta_\lambda \sim O(0.1 - 1)}$ *survives all current bounds.

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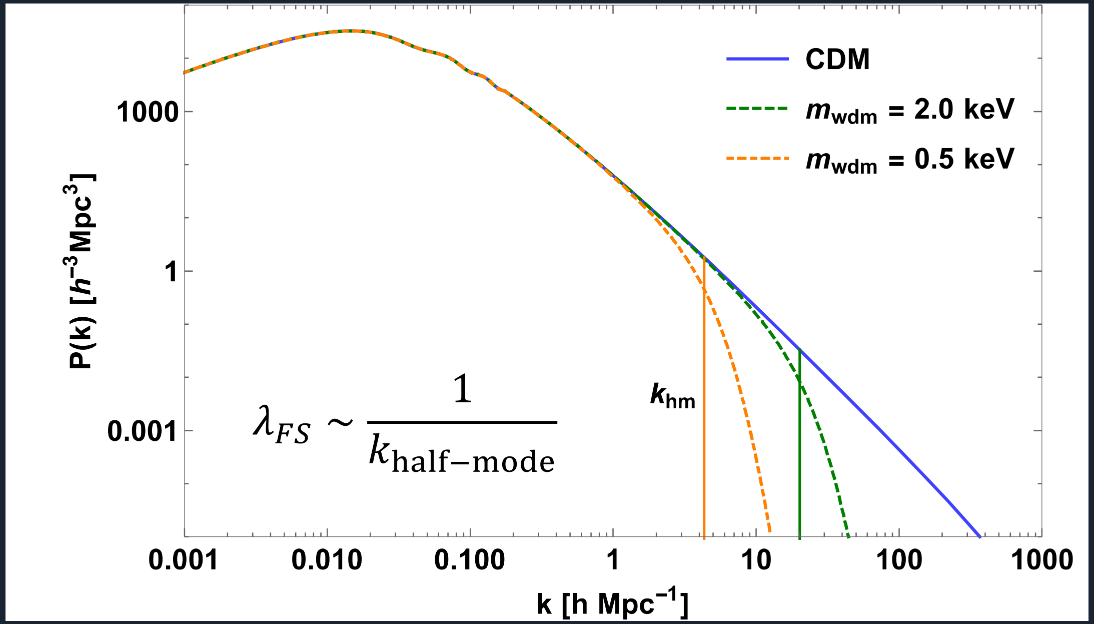
Matter power spectrum with a spatially modulated small-scale cut-off

Warmness of dark matter is encoded in the linear matter power spectrum $P^{\mathrm{lin}}_{\mathrm{WDM}}(k)$, through a suppression of power below the free-streaming scale λ_{FS}. This suppression can be described by the transfer function

$$T_{\mathrm{FS}}(k, \lambda_{FS}) = \left[\frac{P^{\mathrm{lin}}_{\mathrm{WDM}}(k, \lambda_{FS})}{P^{\mathrm{lin}}_{\mathrm{CDM}}(k)}\right]^{1/2}$$



e.g. Matter power spectrum for different DM warmness
MNRAS 481, 1290-1299(2018)

When λ_{FS} is modulated on large scales, the cut-off scale also becomes position dependent: spatially varying cut-off

$$\lambda_{FS} \rightarrow \lambda_{FS}(\boldsymbol{x})$$

Large-scale modulation of small-scale structure formation

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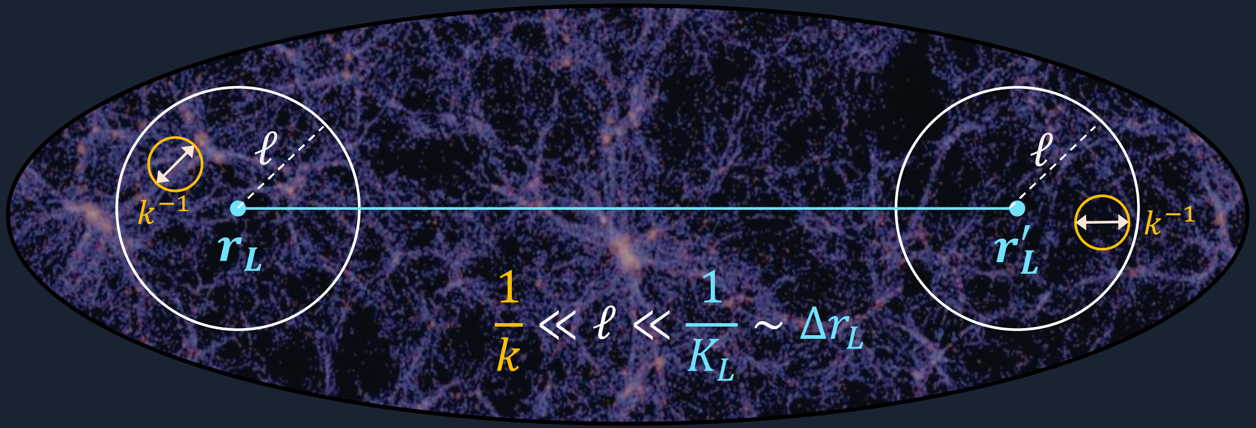
The new observable we propose

If $\delta_\lambda \sim O(0.1\text{–}1)$ is allowed, how do we actually detect it? By measuring the small-scale power spectrum in separate patches and asking whether they are correlated over long distances — effectively a **4-point function of the matter density field**.



Response of P_m to δ_λ

$$\Delta P_m(k, \lambda_{FS}(r_L)) \simeq \lambda_{FS} \frac{dP_m}{d\lambda_{FS}} \delta_\lambda(r_L)$$

Patch-to-Patch Correlation = 4-point function (closely related to the collapsed limit of the trispectrum)

$$P_{PP}(k, K_L) = \lambda_{FS}^2 \left(\frac{dP_m}{d\lambda_{FS}}\right)^2 P_{\delta_\lambda}(K_L)$$

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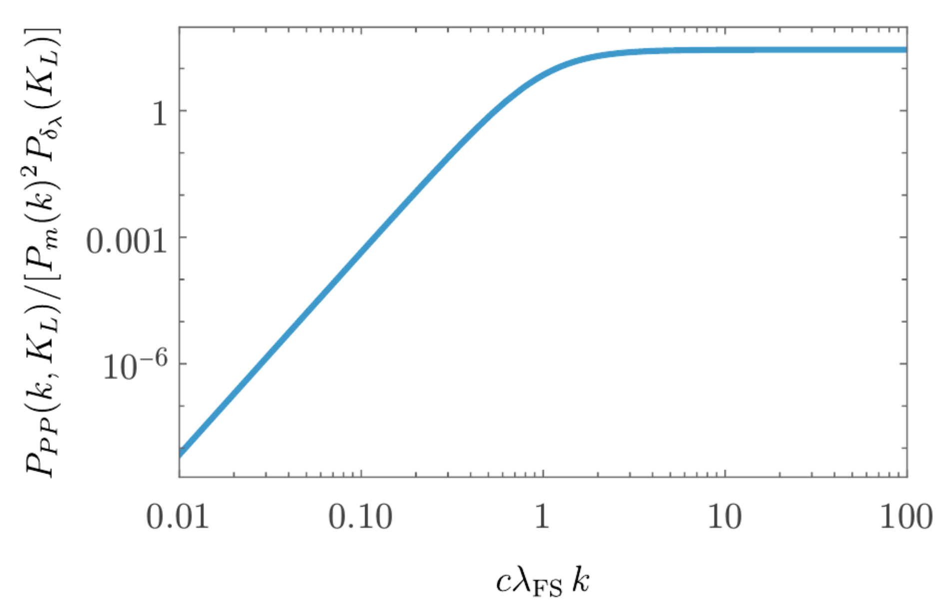
Main result: the 4-point correlation signal

Using a standard WDM transfer function:

$$T_{\rm FS}(k,\lambda_{FS}) \simeq \left(1+(c\lambda_{FS}k)^{\beta}\right)^{\gamma}, \qquad \beta = 2.4, \gamma = -1.1$$

At the characteristic scale $k_{FS} = 1/(c\,\lambda_{FS})$, the patch-to-patch ratio simplifies to:

$$\frac{P_{PP}(k_{FS},K_L)}{P_m(k_{FS})^2} \simeq 10\,P_{\delta_\lambda}(K_L)$$



An O(0.1-1) signal — potentially detectable

Kinetic isocurvature opens a detectable, O(0.1-1)-level signal in a new class of long-range correlations — providing a concrete observational target for future surveys.

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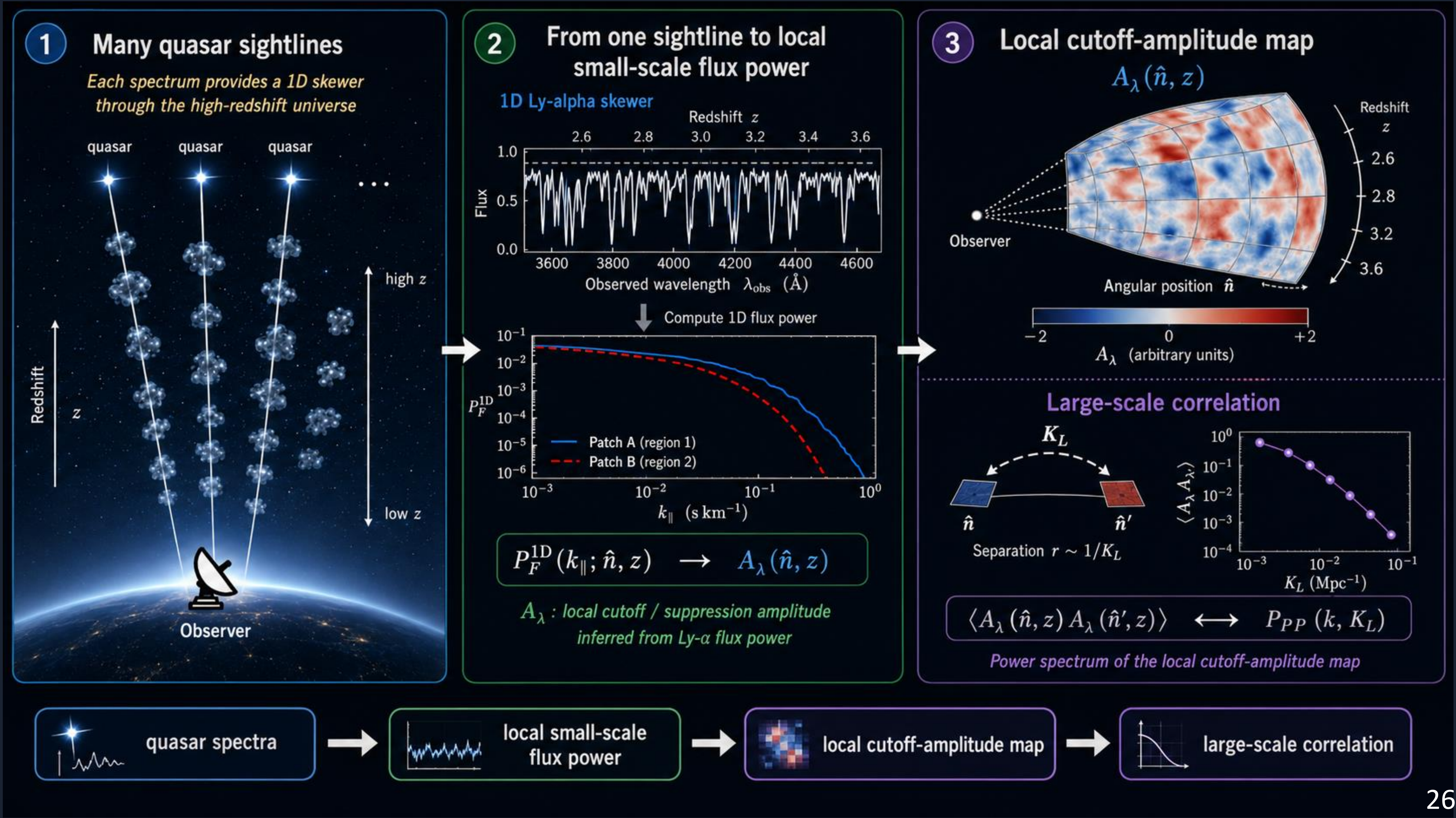
From 4-point statistics to a cutoff-amplitude map



Summary and outlook

01 · FRAMEWORK

A new paradigm

A distinct class of primordial fluctuations driven by momentum. $\delta p \neq 0, \ \delta n = 0.$

02 · MECHANISM

The natural detour

The kinetic contribution to $\delta\rho$ redshifts away, automatically evading standard CMB bounds.

03 · SIGNAL

The observable

Initial momentum dictates λ_{FS}, leaving an O(0.1-1) imprint as patch-to-patch variation in the small-scale power-spectrum.

OPEN FRONTIER

Galaxy surveys and Lyman-α forests offer a direct path to probing DM microphysics through a new class of 4-point statistics at $K_L < 0.01 - 0.1\ Mpc^{-1}$.