Production of Purely Gravitational Dark Matter

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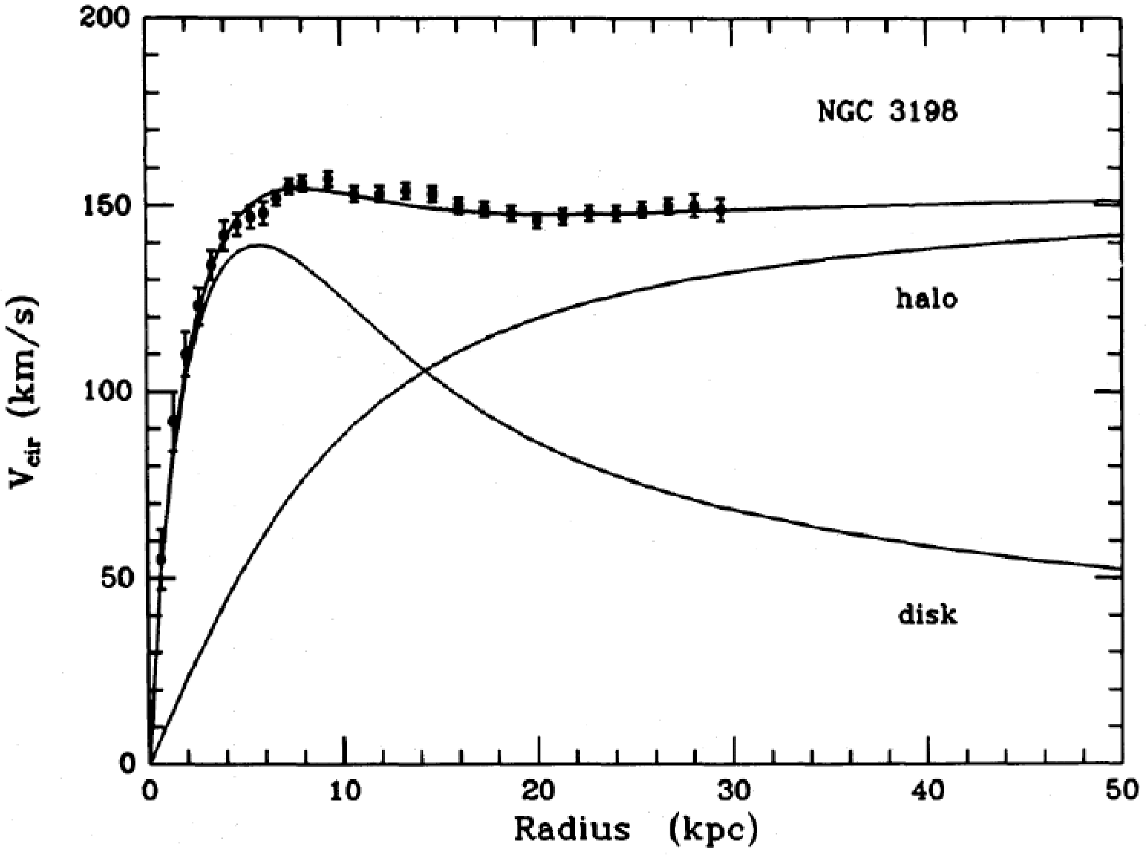
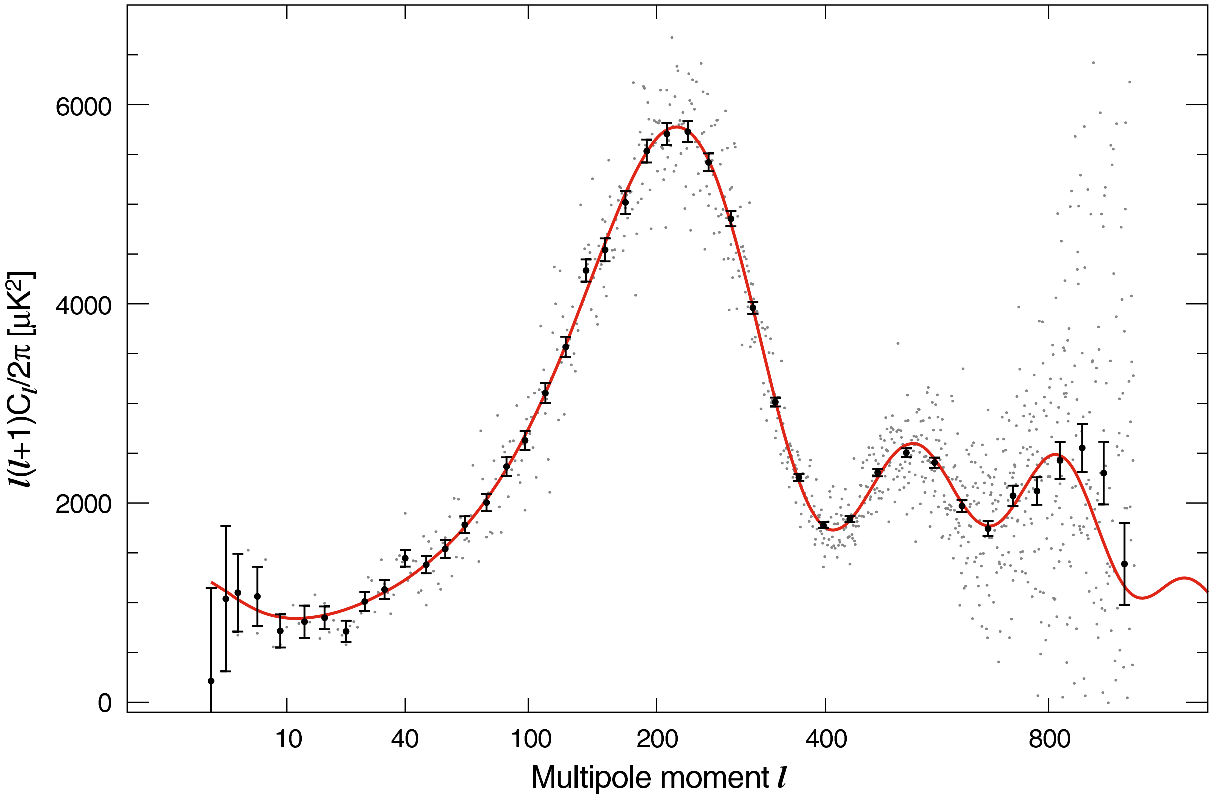

NGC 3198
halo
disk
V_{cir} (km/s)
Radius (kpc)
0
50
100
150
200
0
10
20
30
40
50


$l(l+1)C_l/2\pi$ [μK²]
Multipole moment l
0
2000
4000
6000
10
40
100
200
400
800

Models of dark matter

- WIMP DM

SUSY neutralino	Weak SU(2), sfermion exchange
Z2 scalar	Higgs-portal coupling

- Light particle

Sterlile neutrino	Mixing with active neutrino
Axion	Anomalous interaction suppressed by PQ scale
Hidden photon	Kinetic mixing with photon

- FIMP, SIMP, …

- Purely Gravitational DM (PGDM)   Only gravitational interaction

PGDM

- Real scalar field interacting only through gravity

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2} M_P^2 R - \frac{1}{2} g^{\mu\nu} \partial_\mu \chi \partial_\nu \chi - \frac{1}{2} m_\chi^2 \chi^2 \right)$$

- Several production mechanisms of PGDM
  - Thermal scattering of SM particle with graviton exchange

$$\mathrm{SM} + \mathrm{SM} \to \mathrm{graviton} \to \chi\chi$$

Garny, Sandora, Sloth (2015); Tang, Wu (2016)

  - Gravitational particle creation   Ema, KN, Tang (2018)

This is not neglected even if $m_\chi \gg H_{\rm inf}$: it is active for $m_\chi \lesssim m_{\rm inf}$

Gravitational Particle Production

L.Parker (1969)

- Action of PGDM with FRW background

$$S = \int d\tau d^3x \frac{1}{2}\left[\widetilde{\chi}'^2 - (\partial_i\widetilde{\chi})^2 - m_\chi^{(\mathrm{eff})2}\widetilde{\chi}^2\right],$$

$$\widetilde{\chi} \equiv a\chi$$

$$g_{\mu\nu}dx^\mu dx^\nu = a^2(\tau)(-d\tau^2 + d\vec{x}^2) \qquad m_\chi^{(\mathrm{eff})2} \equiv a^2 m_\chi^2 - \frac{a''}{a}$$

- Effective mass is time-dependent $\longrightarrow$ particle production

Non-conformal particle "feels" background expansion

- Non-adiabatic change of background leads to efficient production

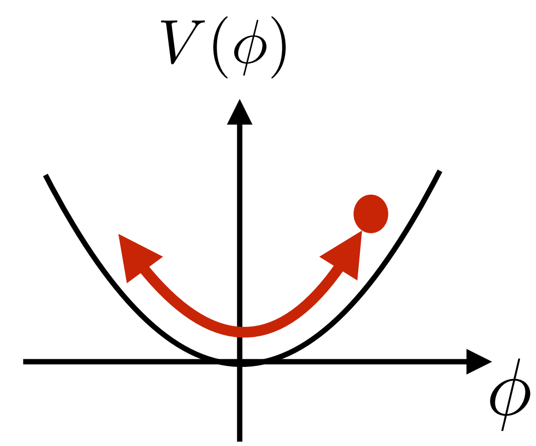
Transition from dS to MD(RD) era: $n_\chi \sim H_{\mathrm{inf}}^3$ — Ford (1986), Chung, Kolb, Riotto (1999)

Inflaton oscillation era: $n_\chi \sim H^3$ — Ema, Jinno, Mukaida, KN (2015)

- Intuitive estimate

  - χ is coupled to inflaton ϕ only through metric

    Note: (massless) scalar is non-conformal



$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2}M_P^2 R - \frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - \frac{1}{2}m_\chi^2\chi^2\right)$$

$$a^2(\tau) \sim \langle a^2(\tau)\rangle\left(1 - \frac{\phi^2(\tau)}{M_P^2}\right)$$

Friedmann eq.

  - "Effective" gravitational inflaton-PGDM coupling

$$\mathcal{L} \sim \frac{\phi^2}{M_P^2}(\partial\chi)^2 \longrightarrow \Gamma(\phi\phi\to\chi\chi) \sim \frac{\phi^2 m_\phi^3}{M_P^4}$$

Particle production in one Hubble time: $n_\chi \sim \frac{\rho_\phi}{m_\phi}\frac{\Gamma}{H} \sim H^3$

Typical momentum is INFLATON MASS (not Hubble): $\frac{k}{a} \sim m_\phi$

Evaluating Gravitational Production

- Quantization

$$\widetilde{\chi}(\tau,\vec{x}) = \int \frac{d^3k}{(2\pi)^3}\left[a_{\vec{k}}\chi_k(\tau) + a^\dagger_{-\vec{k}}\chi^*_k(\tau)\right]e^{i\vec{k}\cdot\vec{x}}, \qquad \left[a_{\vec{k}}, a^\dagger_{\vec{k}'}\right] = (2\pi)^3\delta(\vec{k}-\vec{k}'),$$

Equation of motion: $\chi''_k + \omega_k^2\chi_k = 0, \qquad \omega_k^2 \equiv k^2 + m_\chi^{(\mathrm{eff})2}.$

- General solution

$$\chi_k(\tau) = \alpha_k(\tau)v_k(\tau) + \beta_k(\tau)v^*_k(\tau), \qquad v_k(\tau) \equiv \frac{1}{\sqrt{2\omega_k}}\exp\left(-i\int\omega_k d\tau\right)$$

EoM: $\alpha'_k v_k = \frac{\omega'_k}{2\omega_k}v^*_k\beta_k, \qquad \beta'_k v^*_k = \frac{\omega'_k}{2\omega_k}v_k\alpha_k$

$|\alpha_k(\tau)|^2 - |\beta_k(\tau)|^2 = 1.$ from canonical commutation relation

$\alpha_k(\tau) \to 1, \quad \beta_k(\tau) \to 0$ for $k\tau \to -\infty$ (initial condition)

- Energy density

$$a^4 \rho_\chi = \int \frac{d^3k}{(2\pi)^3} \frac{1}{2} \left[|\chi_k'|^2 + (k^2 + a^2 m_\chi^2)|\chi_k|^2 \right]$$

$$= \int \frac{d^3k}{(2\pi)^3} \frac{\omega_k}{2} (1 + 2|\beta_k|^2)$$ at the adiabatic vacuum $\mathcal{H} \to 0$

Zero-point energy

(renormalized by cosmologcial constant)

UV finite energy density

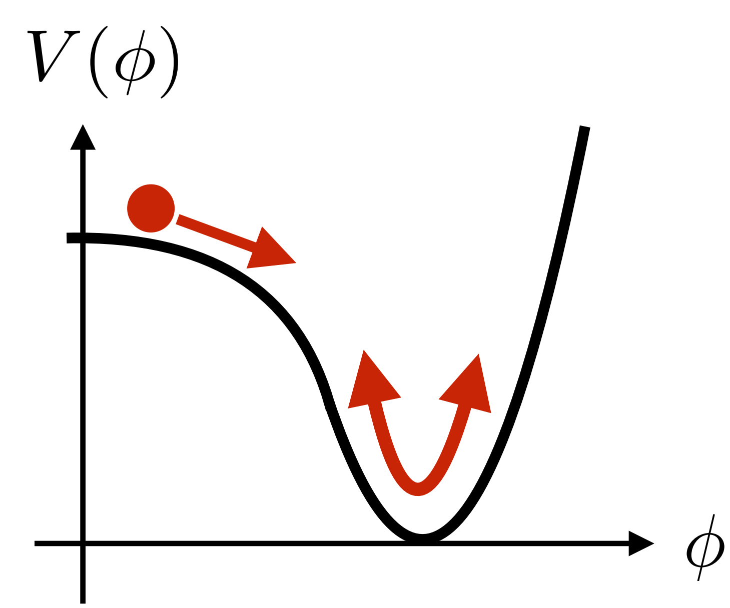
interpreted as particle production

- We can numerically evaluate $f_\chi(k) = |\beta_k|^2$ given inflation model

  - Hilltop inflation

$$V(\phi) = M^4 \left[1 - \left(\frac{\phi}{v_\phi} \right)^n \right]^2 \qquad n = 6$$

$m_\phi \gg H_{\rm inf}$ for $v_\phi \ll M_P$



- Phase space distribution well after inflation

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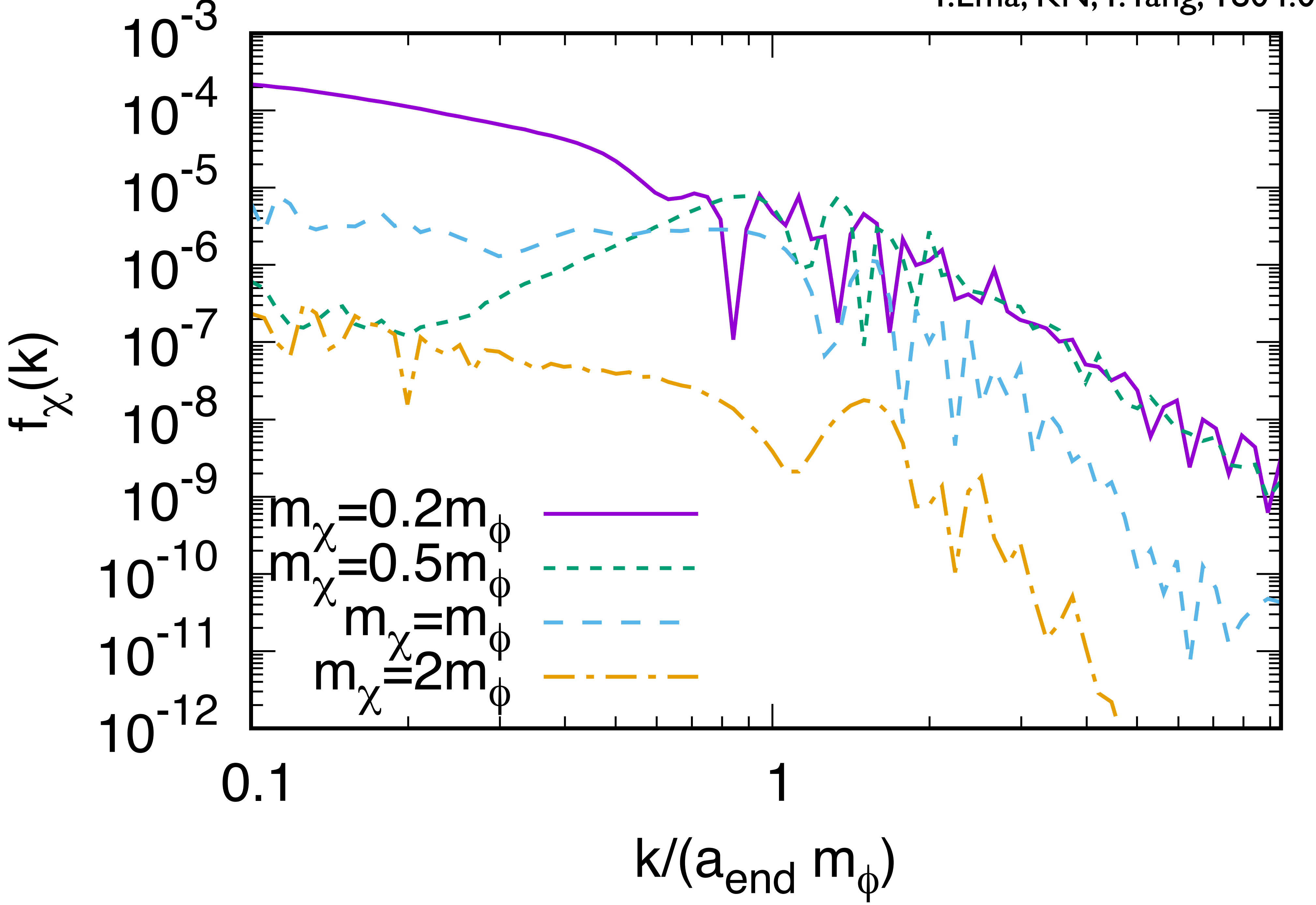

$v_\phi = 0.5 M_P$

$\left(\frac{m_\phi}{H_{\rm inf}} \sim 30\right)$

$a_{\rm end}$: scale factor at the end of inflation

Note: energy density is peaked around $k \sim a_{\rm end} m_\phi$

- Phase space distribution well after inflation

Production around the end of inflation

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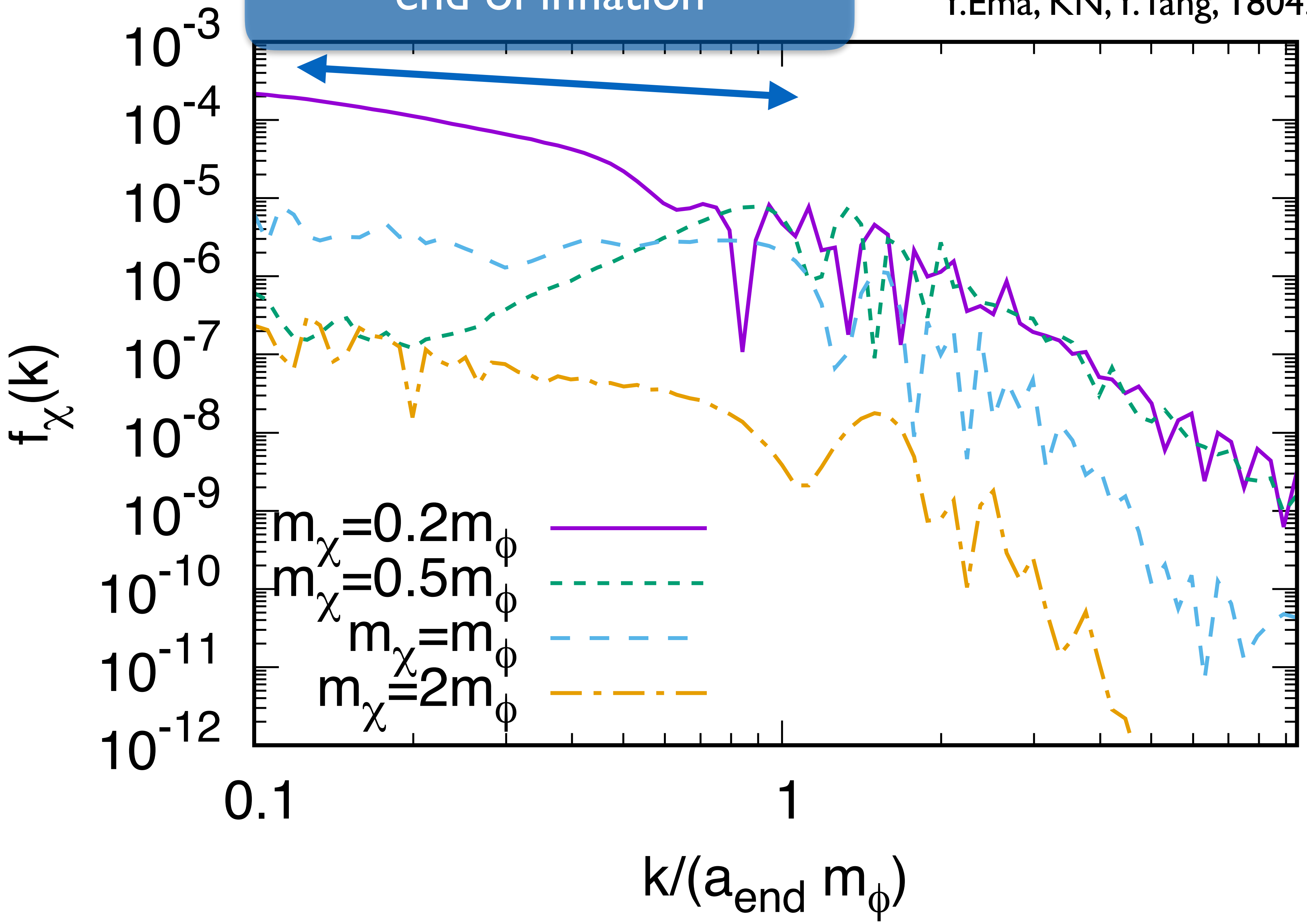

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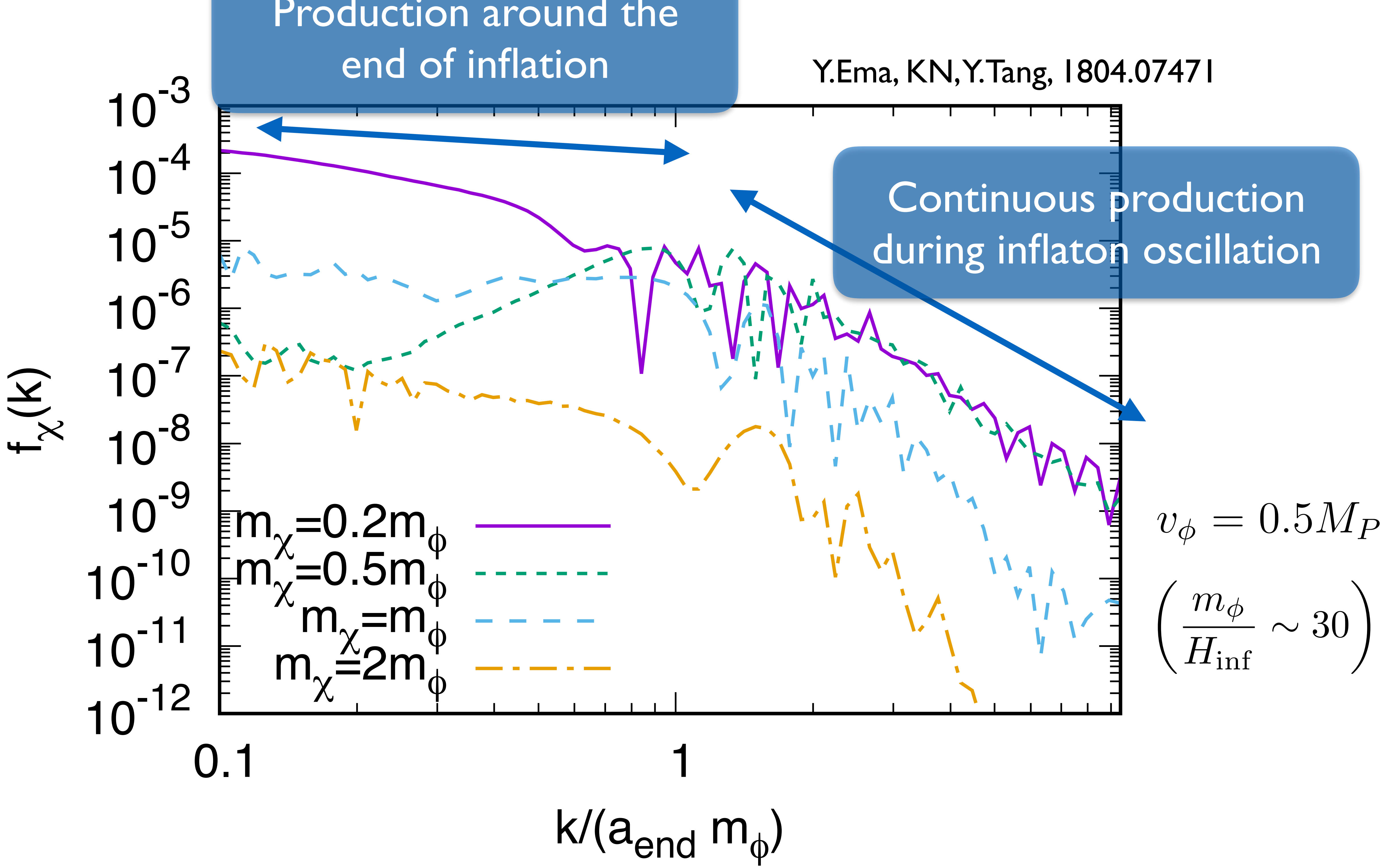


$a_{\rm end}$: scale factor at the end of inflation

Note: energy density is peaked around $k \sim a_{\rm end} m_\phi$

- PGDM energy density from gravitaional production

$$\frac{\rho_\chi^{(\mathrm{GP})}}{s} \sim \frac{\mathcal{C}}{4}\frac{m_\chi H_{\mathrm{inf}} T_{\mathrm{R}}}{M_P^2} \simeq 3\times 10^{-10}\,\mathrm{GeV}\,\mathcal{C}\left(\frac{m_\chi}{10^9\,\mathrm{GeV}}\right)\left(\frac{H_{\mathrm{inf}}}{10^9\,\mathrm{GeV}}\right)\left(\frac{T_{\mathrm{R}}}{10^{10}\,\mathrm{GeV}}\right)$$

In most cases, this is much larger than thermal production $\frac{\mathrm{TP}}{\mathrm{GP}} \sim \frac{T_{\mathrm{R}}^4}{H_{\mathrm{inf}}^2 M_P^2}$

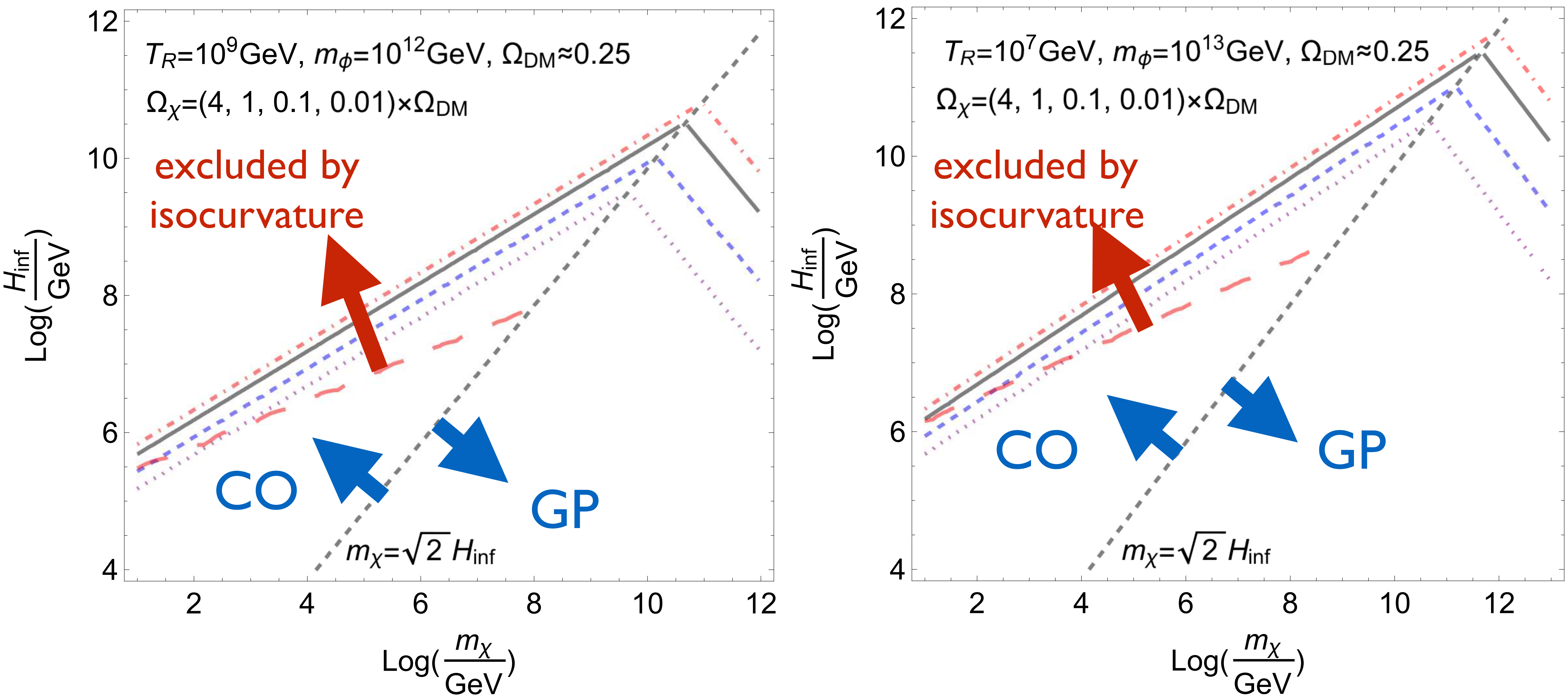
This applies for $m_\chi \lesssim m_\phi$ even if $m_\chi > H_{\mathrm{inf}}$

- PGDM energy density from coherent oscillation

$$\frac{\rho_\chi^{(\mathrm{CO})}}{s} \simeq \frac{T_{\mathrm{R}}}{8}\frac{\langle\chi^2\rangle}{M_P^2} \simeq 8\times 10^{-12}\,\mathrm{GeV}\left(\frac{H_{\mathrm{inf}}}{10^9\,\mathrm{GeV}}\right)^4\left(\frac{10^9\,\mathrm{GeV}}{m_\chi}\right)^2\left(\frac{T_{\mathrm{R}}}{10^{10}\,\mathrm{GeV}}\right)$$

$\langle\chi^2\rangle \simeq \frac{3H_{\mathrm{inf}}^4}{8\pi^2 m_\chi^2}$ is assumed. This applies for $m_\chi \lesssim H_{\mathrm{inf}}$ Linde, Mukhanov (1997)

Constraint from CDM isocurvature perturbation is stringent.



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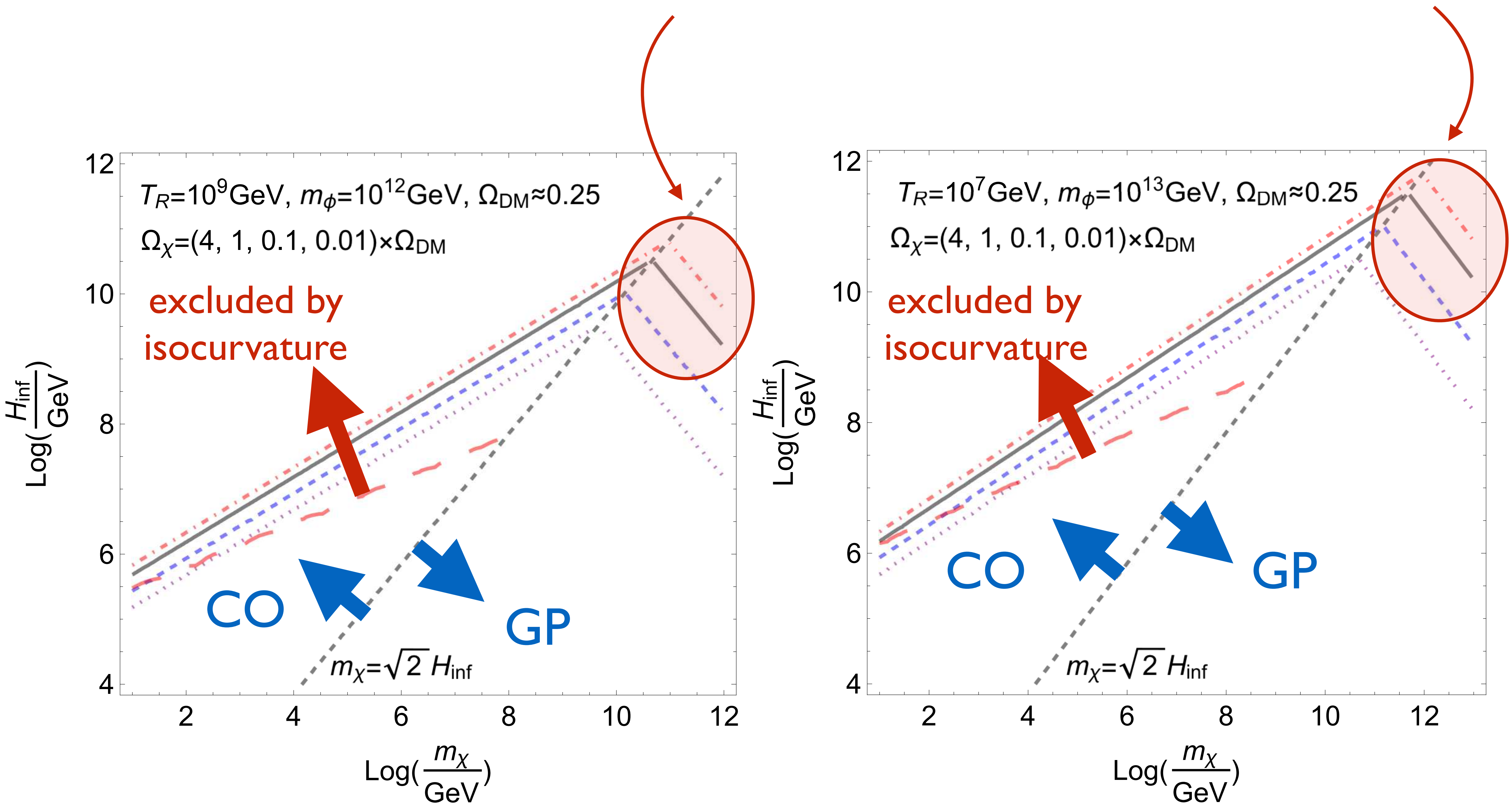
Region of consistent PGDM abundance



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Summary

- “Minimal” dark matter model:
  purely gravitational dark matter (PGDM)

- Abundance of PGDM from gravitational production after inflation is calculated.

- Gravitational production is effective as long as PGDM is lighter than the inflaton mass.

  In most cases it is dominant contribution, compared with e.g. thermal production.

Appendix

Non-minimal coupling

- PGDM nonminimal coupling to gravity

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2}(M_P^2 - \xi\chi^2)R - \frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - \frac{1}{2}m_\chi^2\chi^2\right)$$

- Canonical action in FRW

$$g_{\mu\nu}dx^\mu dx^\nu = a^2(\tau)(-d\tau^2 + d\vec{x}^2)$$

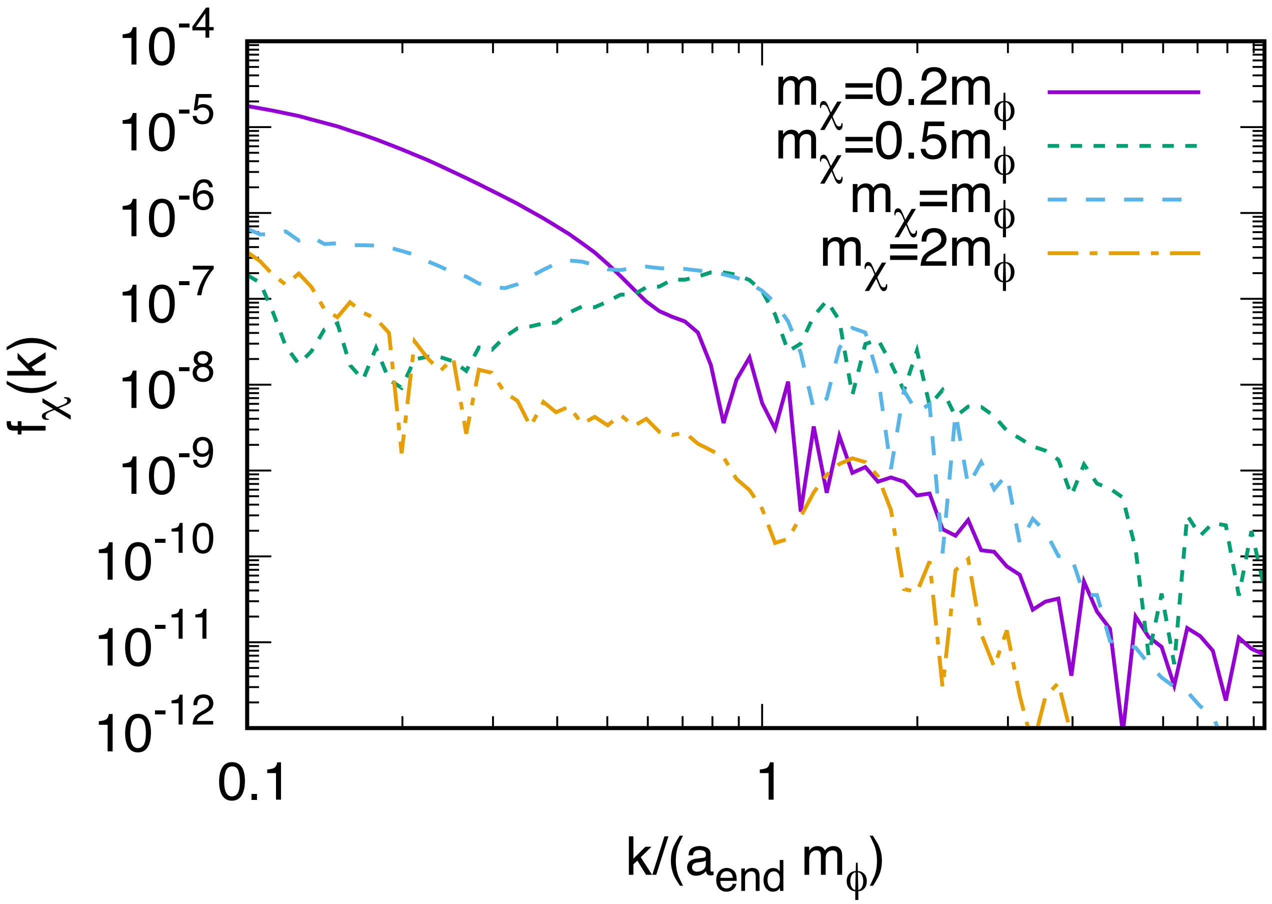
$$S = \int d\tau d^3x \frac{1}{2}\left[\widetilde{\chi}'^2 - (\partial_i\widetilde{\chi})^2 - m_\chi^{(\mathrm{eff})2}\widetilde{\chi}^2\right], \qquad \widetilde{\chi} \equiv a\chi$$

$$m_\chi^{(\mathrm{eff})2} \equiv a^2 m_\chi^2 - (1-6\xi)\frac{a''}{a}$$

- A special case: $\xi = \frac{1}{6}$ (conformal coupling)
- $\xi \gtrsim \frac{m_\phi^2}{H_{\mathrm{inf}}^2}$: tachyonic instability

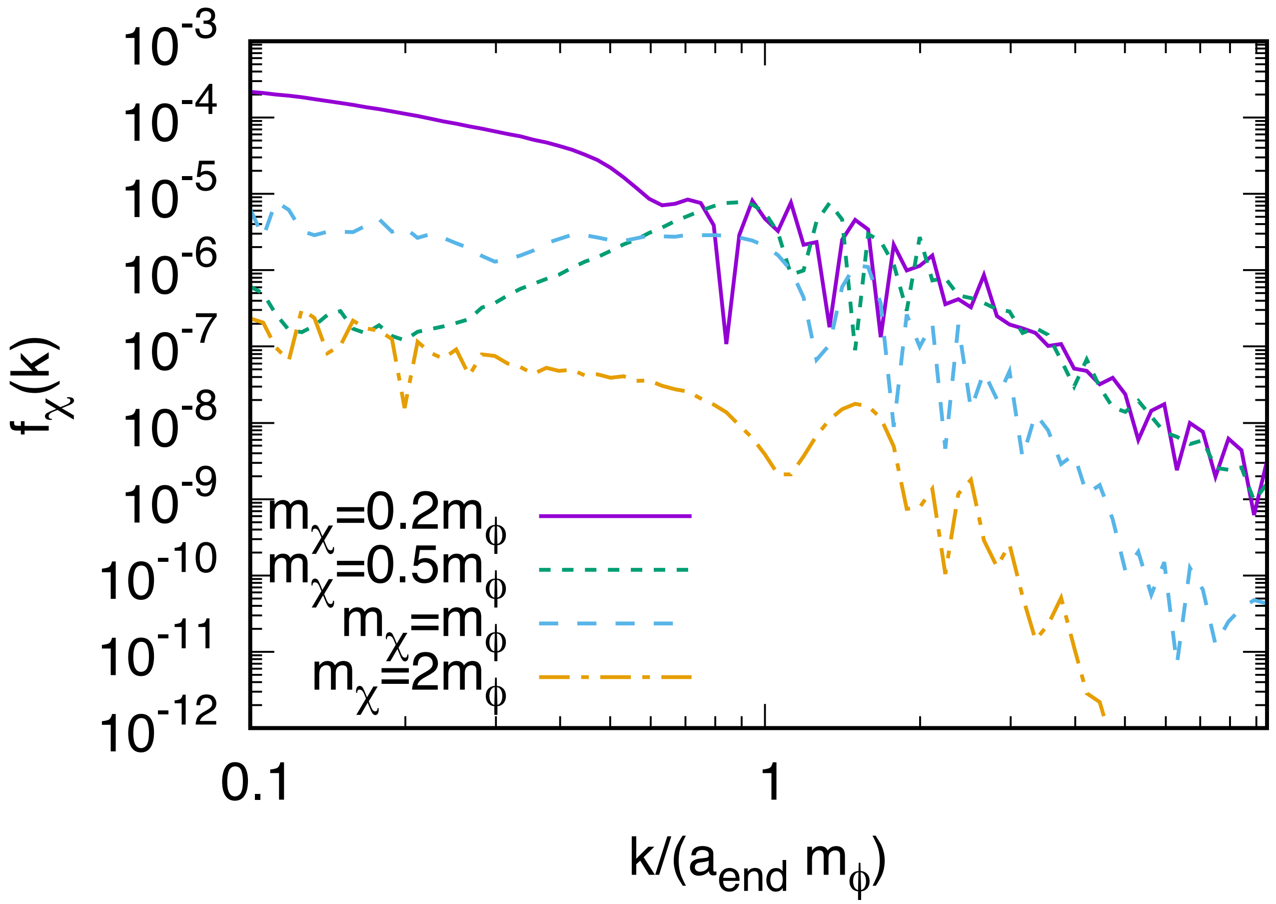
Bassett, Liberati (1998),
Tsujikawa, Maeda, Torii (1999)

Conformal coupling



$$n_\chi \sim H_{\rm inf}^3 \left(\frac{m_\chi}{m_\phi}\right)^4$$

Minimal coupling



$$n_\chi \sim H_{\rm inf}^3$$