ISOCURVATURE AND NON-GAUSSIANITY FROM GRAVITATIONAL PARTICLE PRODUCTION

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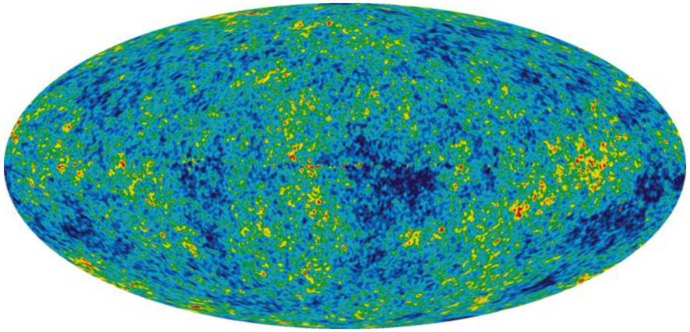
Outline

- Introduction
  - Non-Gaussianity
  - f_{NL}
- Our scenario: The Super Heavy Dark Matter Model
- Conditions to be a viable model
  - Adiabaticity
  - Non-Gaussianity
- The Parameter Space of the SDM Model
- Conclusion

The CMB temperature fluctuation

- Isotropic
- T = 2.725 K
- Temperature fluctuation
  - Small
  - Adiabatic
  - Scale-invariant
  - Nearly Gaussian



From the 5 years WMAP data

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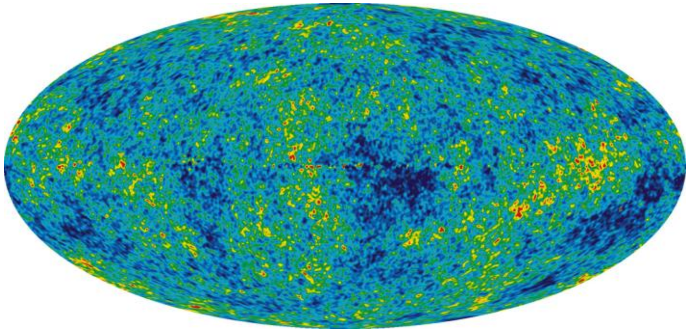

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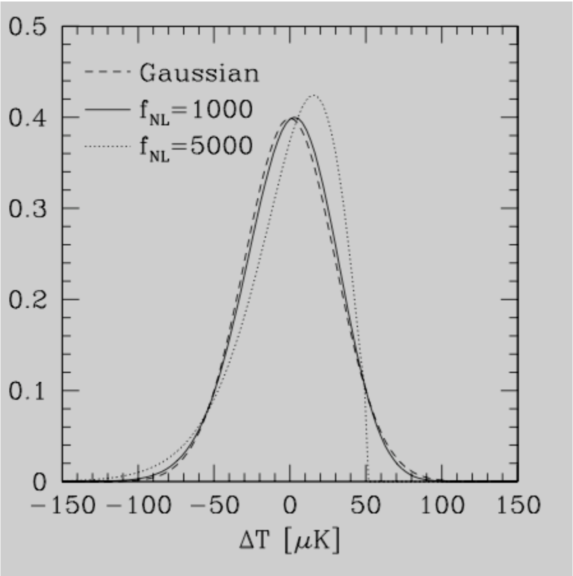


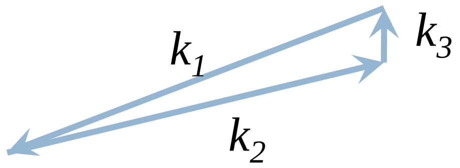
$$\zeta = \zeta_g + \frac{3}{5} f_{\rm NL} \left(\zeta_g^2 - \left\langle \zeta_g^2 \right\rangle \right)$$ (Local-type)

Non-Gaussianities and $f_{\rm NL}$

- The temperature fluctuation is nearly Gaussian, …

- Any clear signals of "Primordial" non-Gaussianities are important for discovering new physics.
  - Bispectrum -> $f_{\rm NL}$, Trispectrum -> $\tau_{\rm NL}$, …

- For example, "simple" inflation models cannot generate large non-Gaussianities. (Maldacena, 2003) (Seery et al., 2005)
  - Einstein GR, Single field, Bunch-Davies vacuum, Slow-roll
  - In the squeezed configuration,
    - $f_{\rm NL} \sim O(1-n_s) << 1$



SDM Isocuvature from Particle Production

- The slow-roll inflation is effectively driven by the inflaton ϕ and ζ originates from the vacuum fluctuation of it during the inflation.

- A massive free scalar field X, super-heavy dark matter(SDM) oscillating around zero value gives rise to isocurvature by gravitational particle production.
  - No interaction other than gravitational interaction
  - Minimally coupled to gravity

- ***Large non-Gaussianity*** maybe obtained from the isocurvature perturbation.

SDM Isocuvature Model

Inflation | **Reheating** | **RD/SBB**

Inflaton ϕ → decays → γ, ν, b, CDM

SDM X → remains → CDM (X)

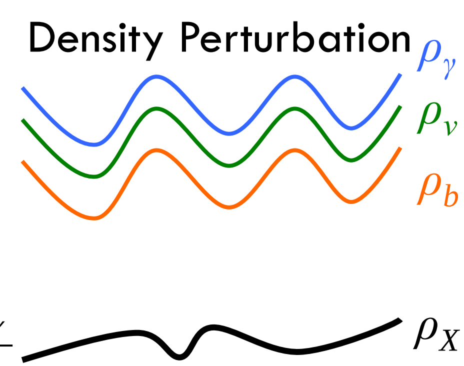
Gravitational Particle Production

$\delta\rho_\phi$ → generates →

Adiabatic $\zeta \propto \frac{\delta\rho}{\rho}$

Isocurvature $S = \frac{\delta\rho_{\rm CDM}}{\rho_{\rm CDM}} - \frac{3\delta\rho_\gamma}{4\rho_\gamma}$

$\delta\rho_X$



(Dunkley et al., 2005)
(Chung et al., 2005)

Adiabaticity and Correlation $<\zeta S>$

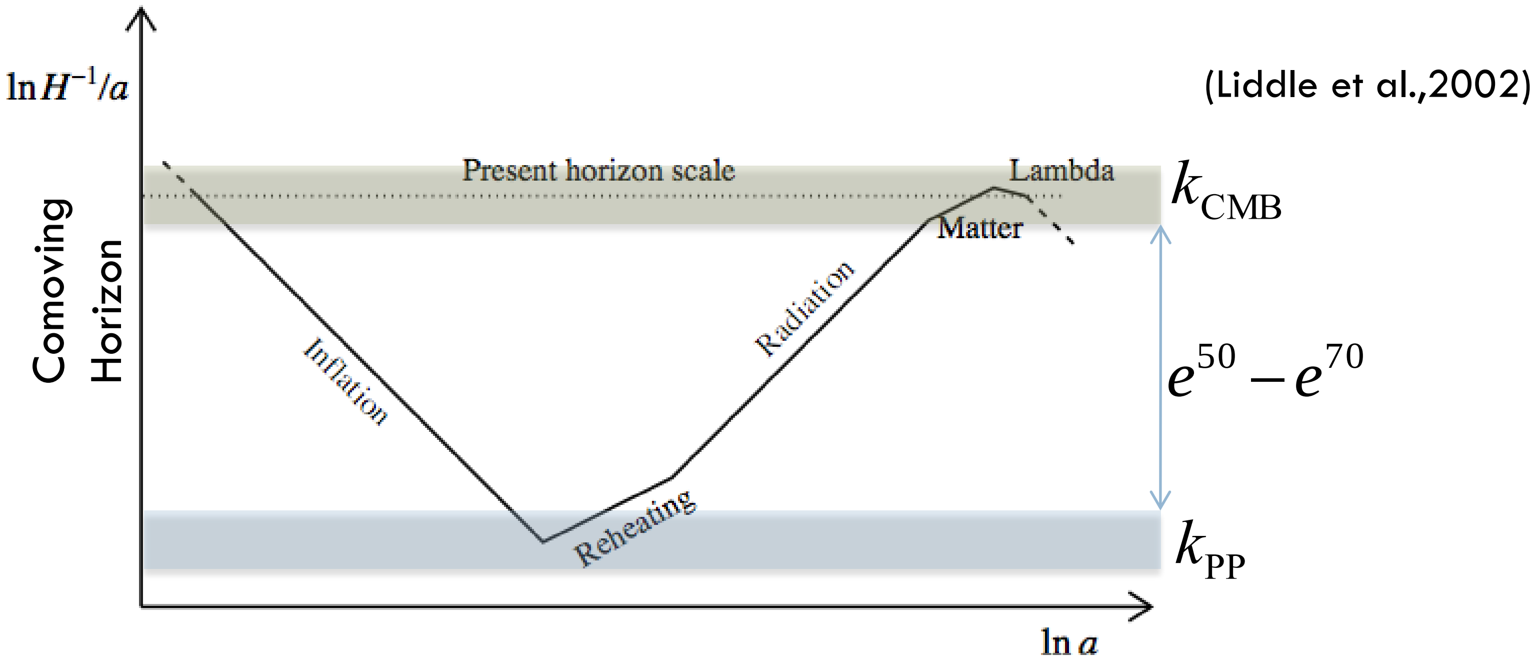
- From observation

(Komatsu et al., 2010)

$$\text{Adiabaticity}\,\alpha \equiv \frac{\Delta_S}{\Delta_\zeta + \Delta_S} \sim \frac{\langle SS \rangle}{\langle \zeta\zeta \rangle} << 1 \qquad \alpha \le \begin{cases} 0.07 & \text{for uncorrelated } \left(\langle \zeta S \rangle = 0\right) \\ 0.004 & \text{for fully-correlated } \left(\langle \zeta S \rangle = -1\right) \end{cases}$$

- Correlation $<\zeta S>$ of the SDM Model?
  - ~~SDM Model~~ if $<\zeta S> = \pm 1$ $\quad \because \langle \zeta S \rangle \sim \sqrt{\alpha}$
  - $S \sim \delta\rho_X/\rho_X$ => $\delta\rho_X$ under ζ
    - $\langle \hat{\rho}_X \rangle$ is divergent.
      => Requires consistent renormalization with GR
    - Scale separation: k_{CMB} vs. $k_{\mathrm{p.p.}}$ …

Particle Production under ζ



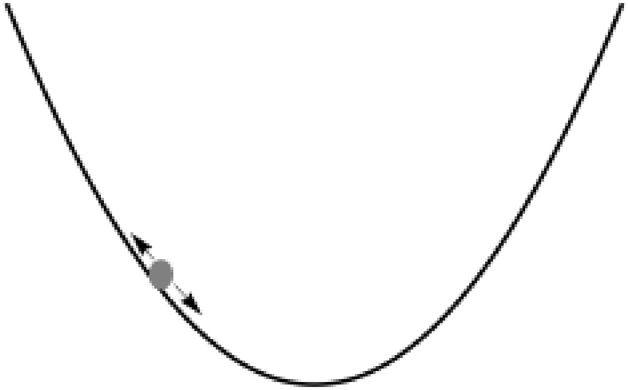
- When particle production is considered:
  - the metric perturbation is nearly homogeneous.
  - ζ is almost constant.

$\Rightarrow$ *ζ and S are decoupled!* $\langle \zeta S \rangle = 0$

Possibility of Large non-Gaussianity

Inflaton | **SDM**

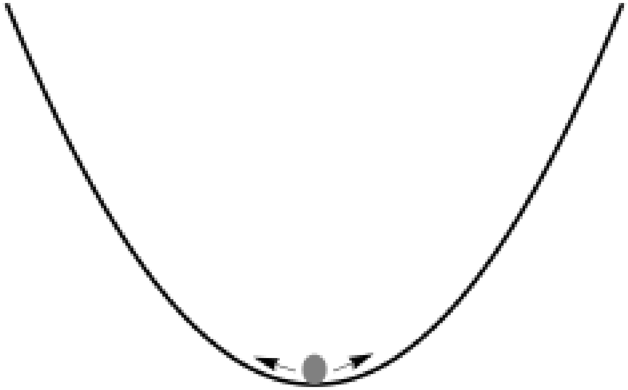
$V(\phi)$ $\quad \phi = \bar{\phi} + \delta\phi$



$\delta\rho_\phi \propto V'(\phi)\delta\phi$

$\Rightarrow \delta\rho_\phi$ is Gaussian.

$V(X)$ $\quad X = \delta X$



$\delta\rho_X \propto X^2$

$\Rightarrow \delta\rho_X$ is not Gaussian.

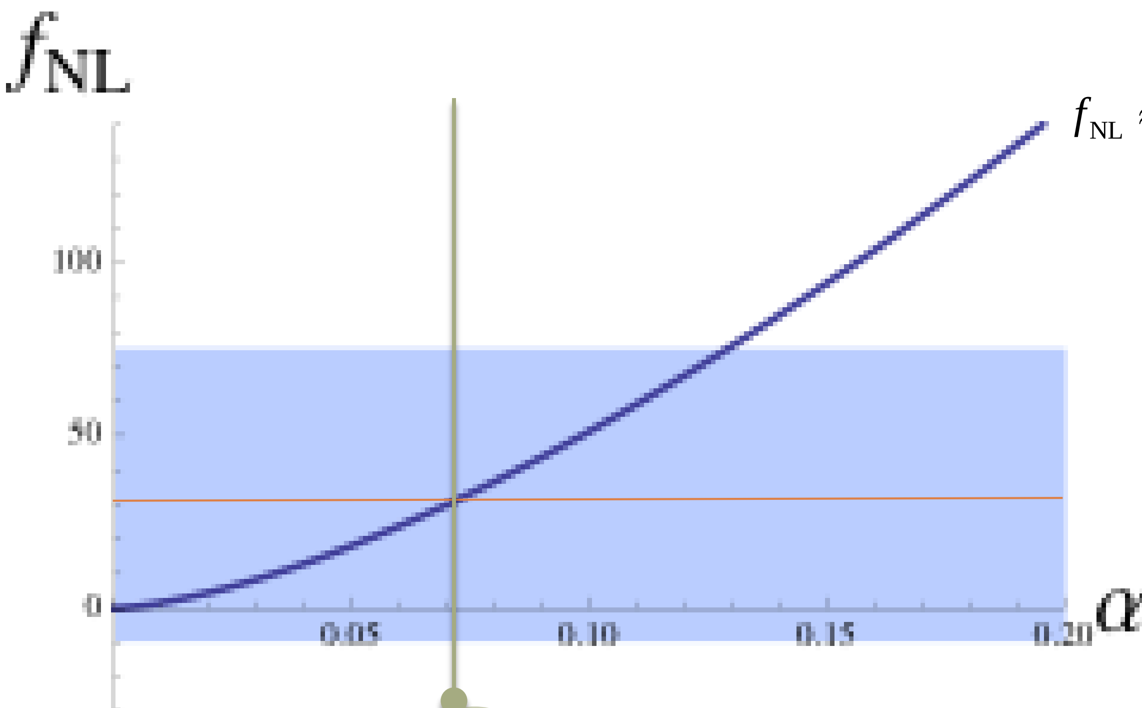
Quadratic type

$\delta\phi$, X becomes classical Gaussian random variables after the horizon exit.

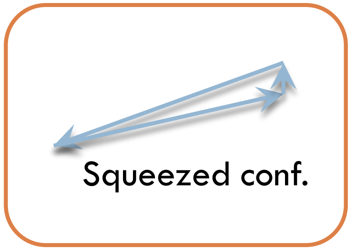
Non-Gaussianity by SDM Isocurvature

- Quadratic-type Model

$$S \approx \frac{m_X^2\left(X^2 - \langle X^2 \rangle\right)}{\rho_X^2}, \quad \langle X_k X_{-k} \rangle \propto \left(\frac{k}{k_0}\right)^{n_X - 1}$$



$$f_{\rm NL} \approx 30\left(\frac{\alpha}{0.07}\right)^{3/2}$$



WMAP Hint

$$-10 < f_{\rm NL} < 75 \ (95\% \ \mathrm{C.L.})$$

$$\text{Adiabaticity}\ \alpha \equiv \frac{\Delta_S}{\Delta_\zeta + \Delta_S} \leq 0.07$$

Explicit Calculation of S

Two Point Correlator

$$\ddot{X}_{\mathbf{k}} + 3H\dot{X}_{\mathbf{k}} + \frac{k^2}{a^2}X_{\mathbf{k}} + m_X^2 X_{\mathbf{k}} = 0$$

with Bunch - Davies Vacuum

$$X_{\mathbf{k}} \to \frac{\sqrt{a}}{\sqrt{\omega_k}} e^{-i\omega_k t} \text{ as } \frac{k}{aH} \to \infty$$

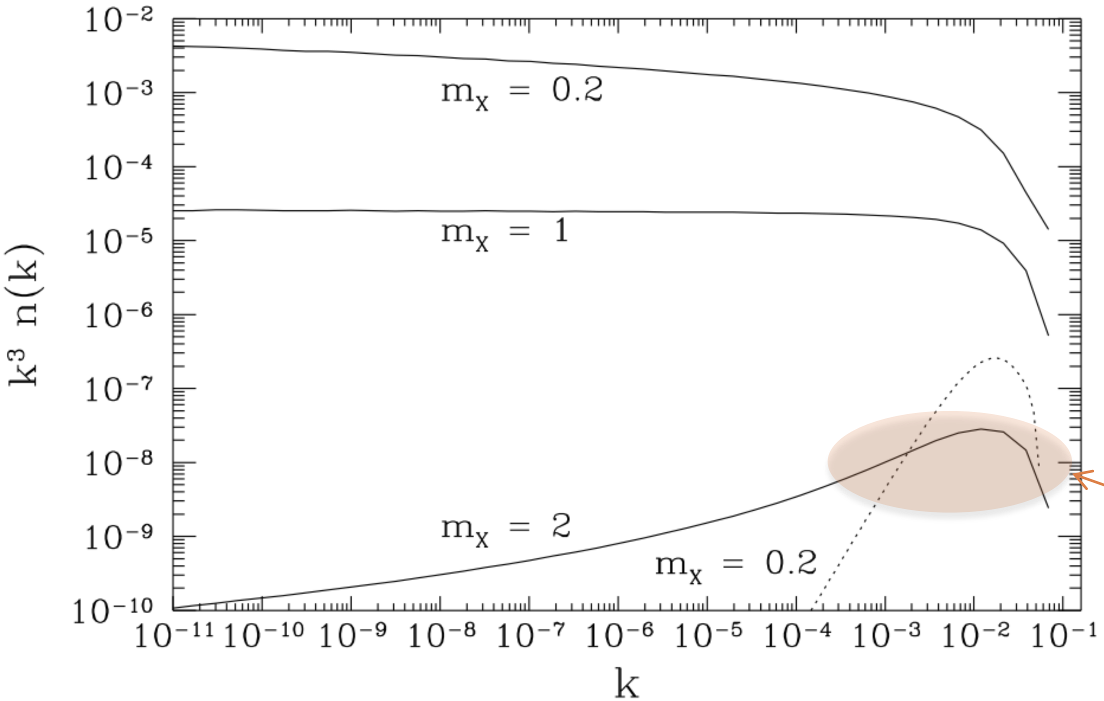
$$S = \frac{\delta\rho_X}{\rho_X} \approx \frac{m_X^2 :X^2:}{\rho_X} \Rightarrow \langle SS \rangle = \frac{m_X^2 \langle :X^2::X^2: \rangle}{\rho_X^{\ 2}}$$

Energy Density by Gravitational Particle Production

Gravitational Particle Production

- The number density is dependent on the model of the inflation and how it ends.

- In particular, *the $m^2\phi^2$ model*



(Chung et al., 1998)
(Kuzmin et al., 1999)

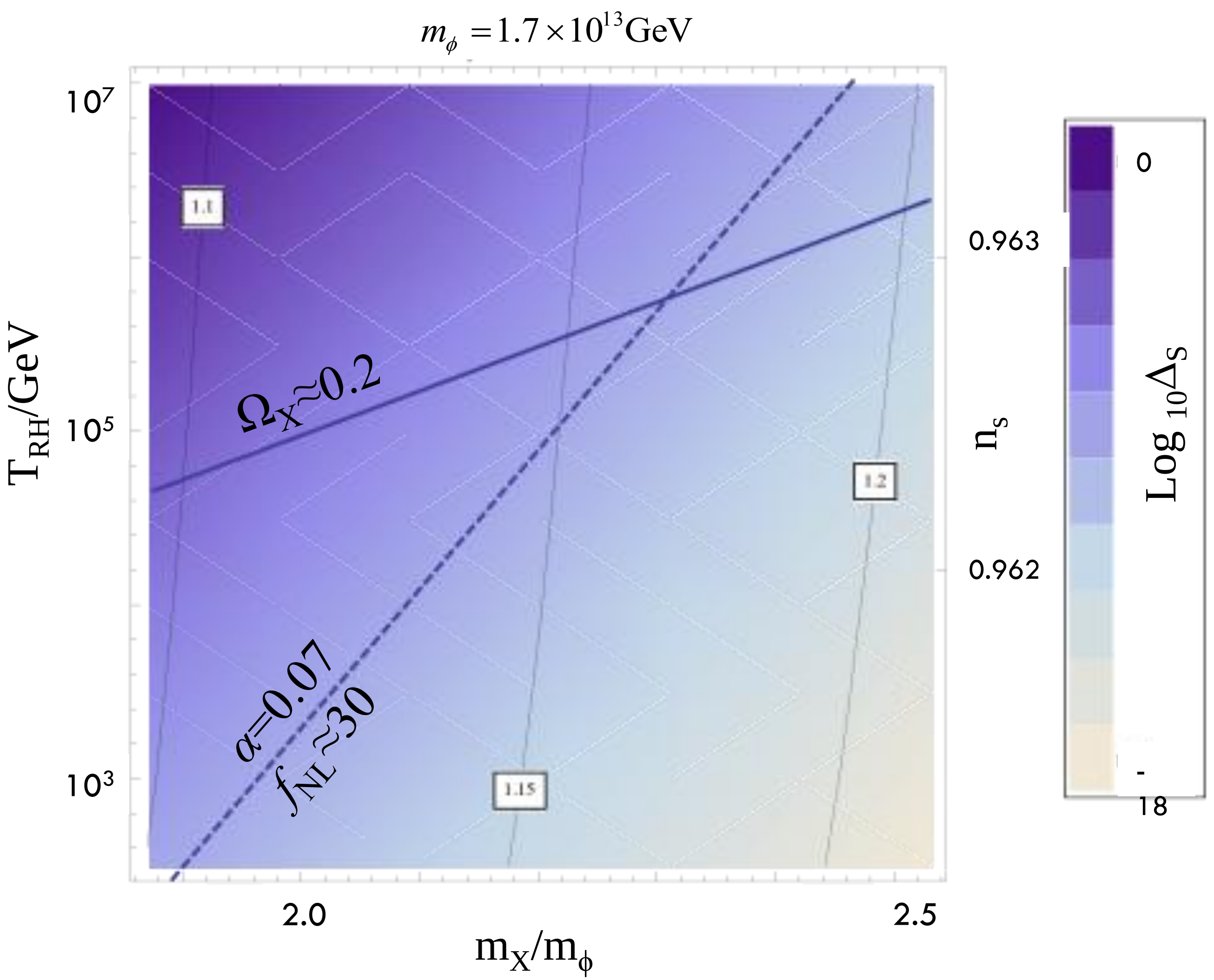
$$\frac{\rho_X}{\rho_\phi} \approx 10^{-10}\frac{m_X}{m_\phi} m_{13}^2 \exp\left(-2\pi\frac{m_X}{m_\phi}\right),$$

where $m_{13} \equiv m_\phi / 10^{13}\mathrm{GeV}$

Dominant contribution:
The modes k ~ H at the end of the inflation.

Isocurvature Powerspectrum

- Parameter Plot



$$\Delta_S^{\mathrm{CDM}}(k) \cong \frac{k^3}{2\pi^2}\frac{P_{\delta\rho_X}(k)}{\rho_X^{\ 2}}\omega_X,$$

$$\omega_X \equiv \frac{\Omega_X}{\Omega_{\mathrm{CDM}}}$$

Isocurvature Powerspectrum

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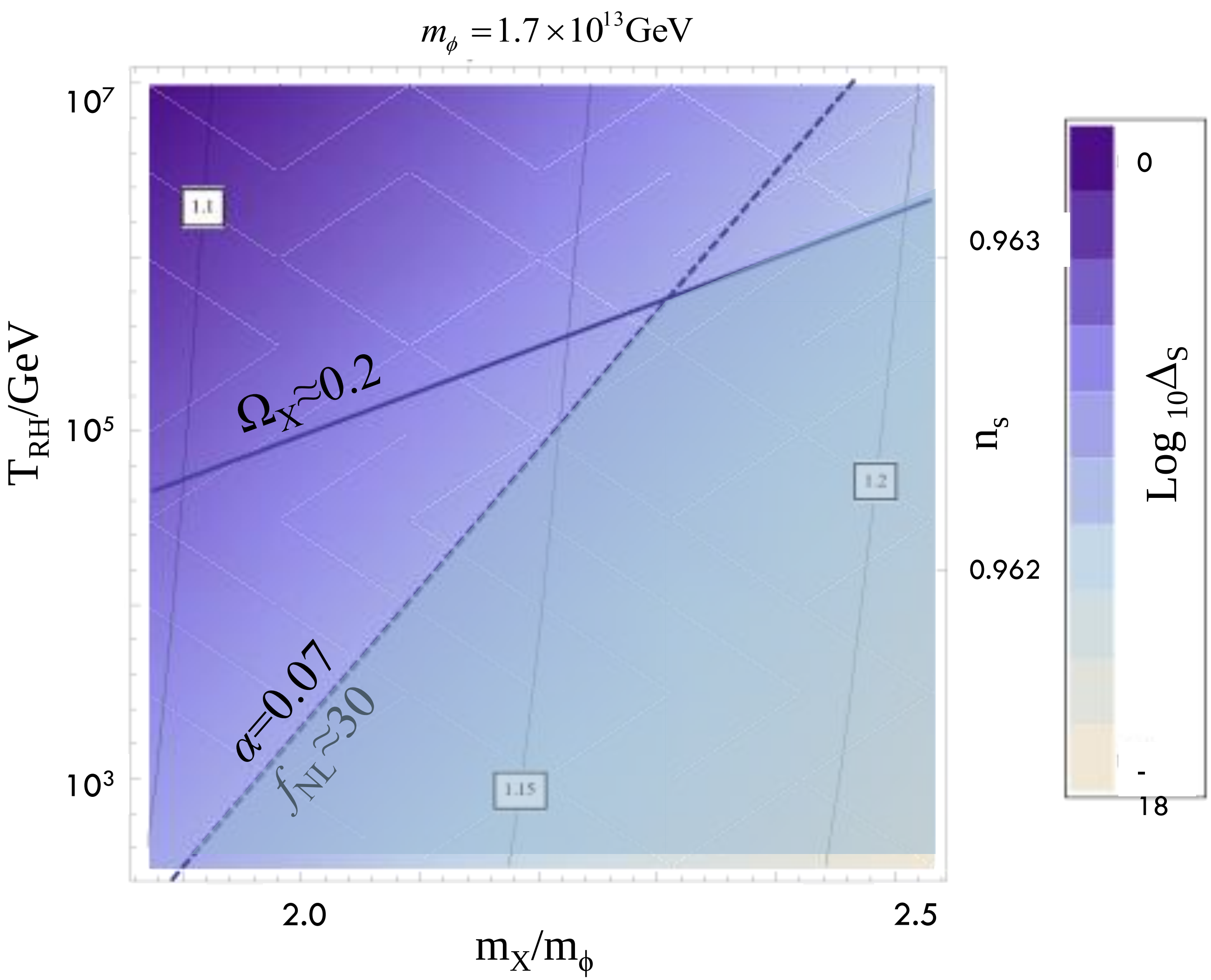

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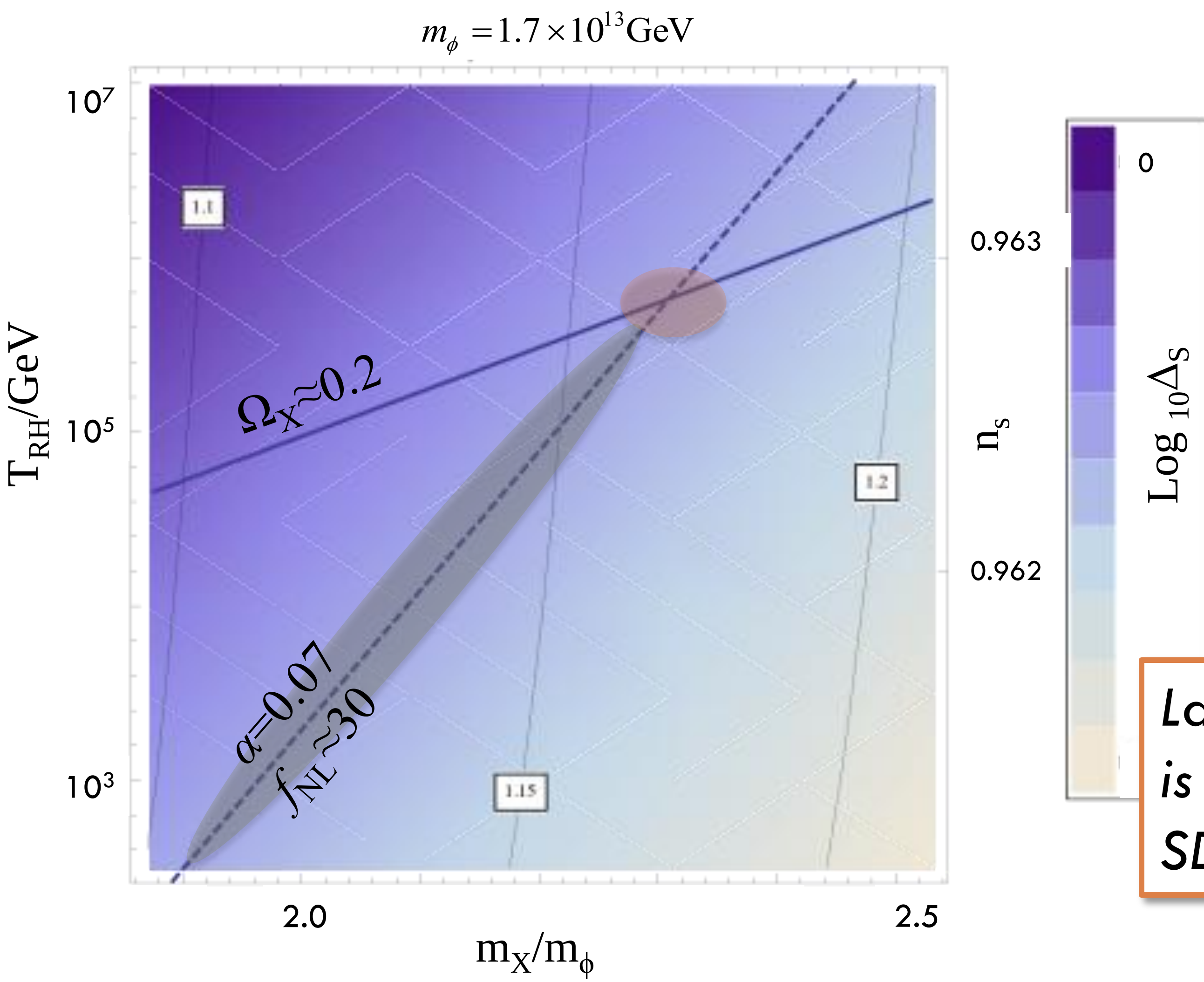

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Large non-Gaussianity is a general feature of SDM Isocurvature!

Conclusion

- Isocurvature Perturbation seeded by gravitational particle production is a uncorrelated-type quadratic model.
- In general, it can generate large non-gaussianity, $f_{NL} \sim 30$ for the squeezed configuration
  - if X solely contributes CDM, $m_X \sim 2.3\, m_\phi$ ($m_X \sim H_e$).
  - if X is a component of CDM, $m_X < 2.3\, m_\phi$.
    - $T_{\mathrm{RH}} < 10^6\,\mathrm{GeV}$
- If $m_X > 2.3\, m_\phi$, not observable in CMB.