

LIGHT AXINO DARK MATTER: *FREEZE-IN PRODUCTION, DECAY & LYMAN-ALPHA FOREST CONSTRAINTS*

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based on

arXiv:1707.02077, 1707.06418

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IBS-Dark World

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AXINO

- ***Supersymmetry+Peccei-Quinn Symmetry:***
 - SUSY solves the gauge hierarchy & PQ solves strong CP
 - Dark Matter candidates: neutralino & axion
- ***Axino Dark Matter:***
 - fermionic SUSY partner of axion
 - becomes massive with SUSY breaking
 - **keV mass is possible:** (warm) *Dark Matter*
- ***Signal?***
 - too weak to be detected: suppressed by $\sim 10^9$ GeV
 - *what if it decays?*
 - *affects matter power spectrum?*

X-RAY LINE?

- 3.5 keV X-ray line excess

Bulbul, Markevitch, Foster, Smith, Lowenstein, Randall (2014)

Boyarsky, Ruchayskiy, Iakubovskyi, Franse (2014)

- Criticism:

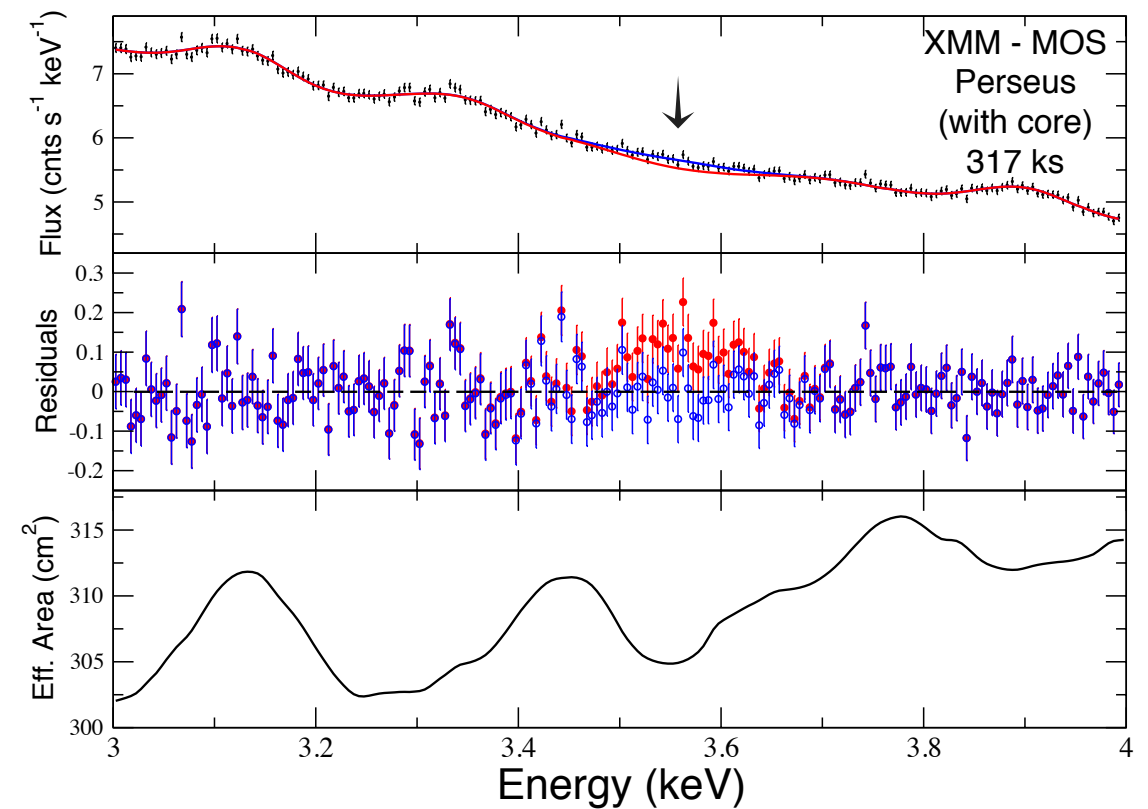
K XVIII explanation

No signal from dSph, stacked galaxies and groups, M31

Morphology study

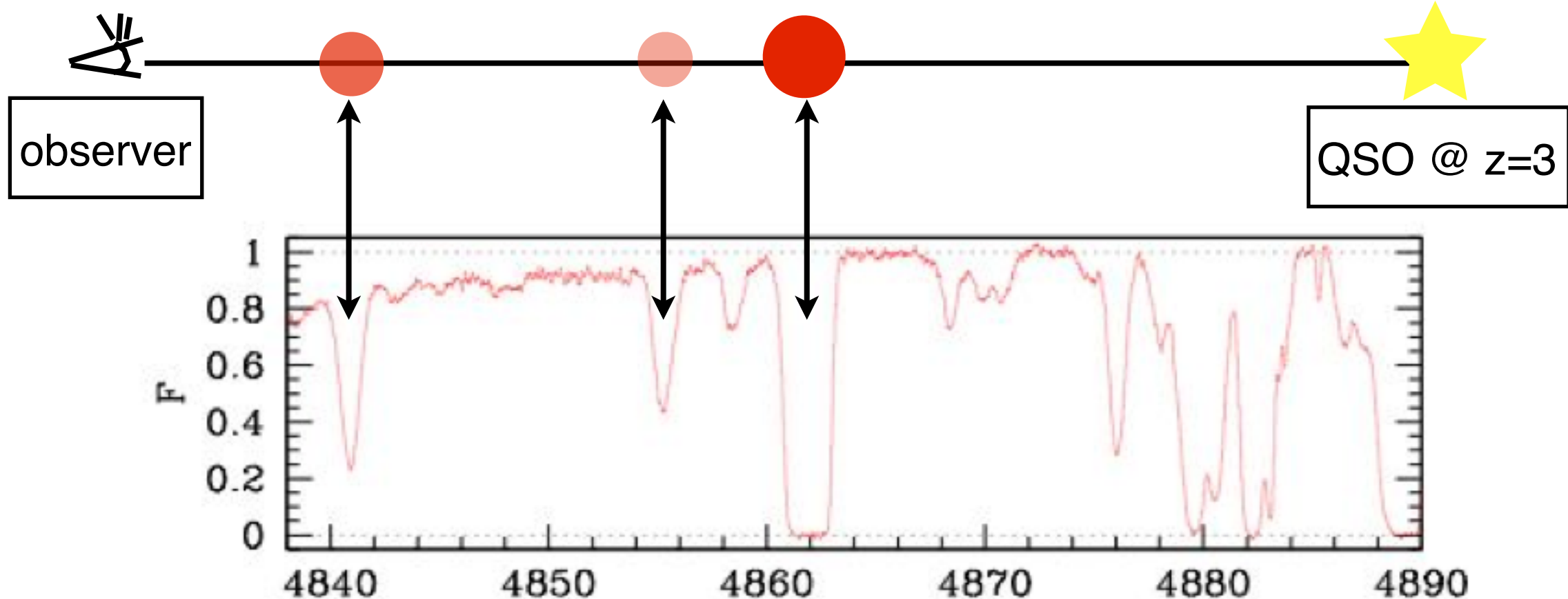
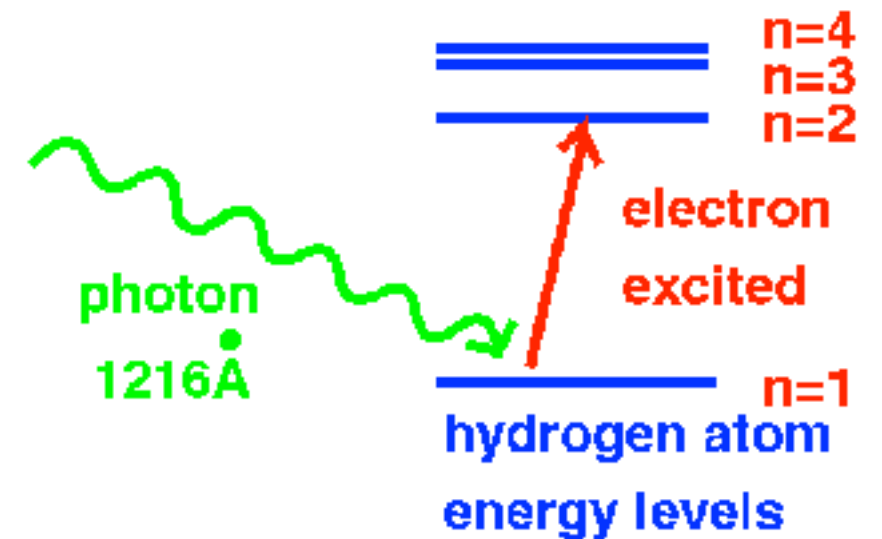
- In this study,

We take 7 keV as a benchmark point (and a possible signal) for light axino study.



LYMAN-ALPHA FOREST

absorption intensity/frequency
↔ HI distribution along the line-of-sight



LYMAN-ALPHA FOREST

- Improving constraints on “warm dark matter mass”

$$m_{\text{WDM}} \gtrsim 2.0 \text{ keV} \quad \text{Viel, Lesgourgues, Haehnelt, Matarrese, Riotto (2005)}$$

$$m_{\text{WDM}} \gtrsim 3.3 \text{ keV} \quad \text{Viel, Becker, Bolton, Haehnelt (2013)}$$

$$m_{\text{WDM}} \gtrsim 4.09 \text{ keV} \quad \text{Baur, Palanque-Delabrouille, Yche, Magneville, Viel (2016)}$$

$$m_{\text{WDM}} \gtrsim 5.3 \text{ keV} \quad \text{Iršič et al. (2017)}$$

- Warm Dark Matter**

Ly-alpha constraints assume the Fermi-Dirac dist. and observed DM density

$$\Omega_{\text{WDM}} h^2 = \left(\frac{m_{\text{WDM}}}{94 \text{ eV}} \right) \left(\frac{T_{\text{WDM}}}{T_\nu} \right)^3 = 7.5 \left(\frac{m_{\text{WDM}}}{7 \text{ keV}} \right) \left(\frac{106.75}{g_*^{\text{WDM}}} \right)$$

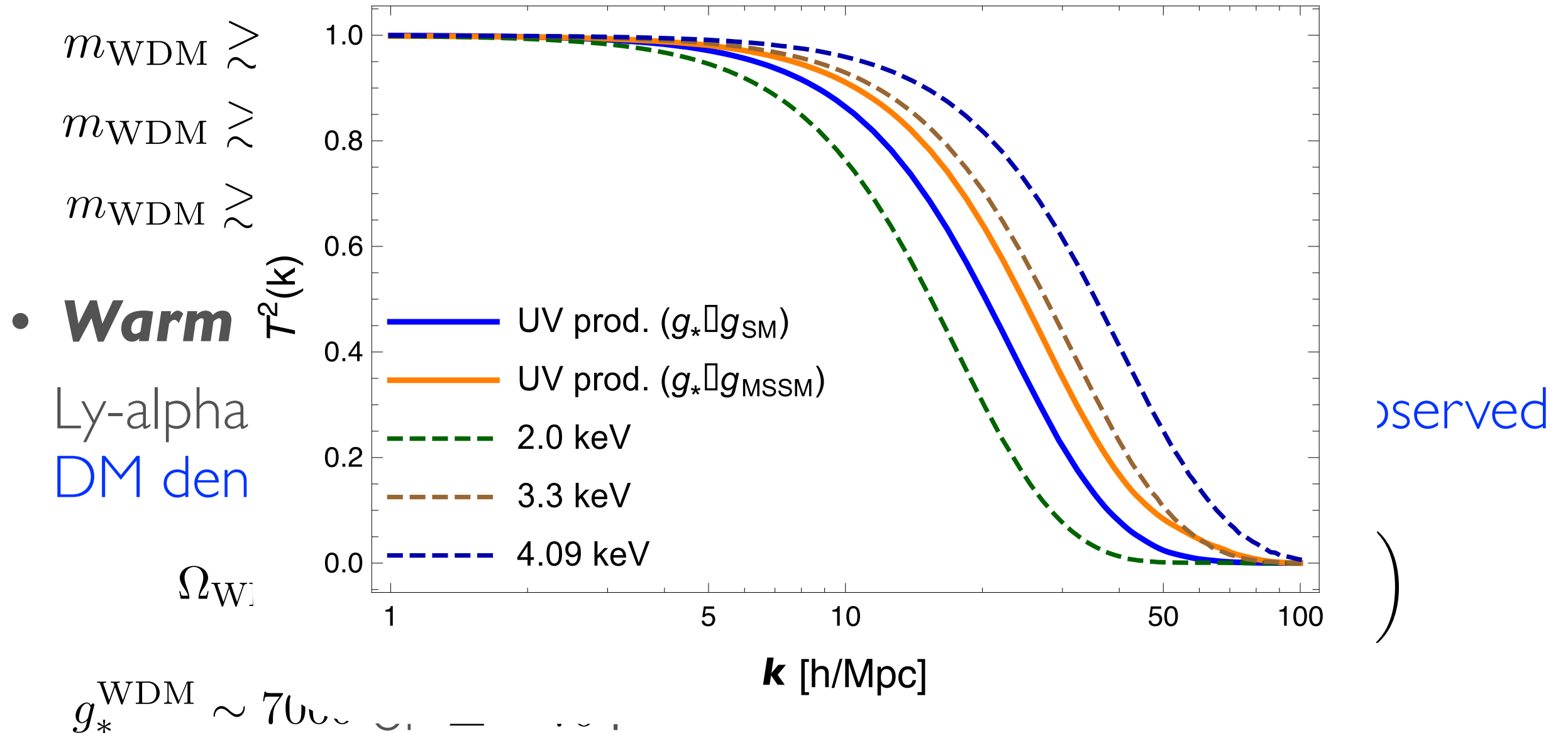
$$g_*^{\text{WDM}} \sim 7000 \text{ or } \Delta \sim 70 ?$$

➡ need *linear matter power spectrum*

LYMAN-ALPHA FOREST

- Improving constraints on “warm dark matter mass”

$$m_{\text{WDM}} \gtrsim 2.0 \text{ keV} \quad \text{Viel Lesgourgues Haehnelt Matarrese Riotto (2005)}$$



➔ need *linear matter power spectrum*

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1. Introduction
2. SUSY DFSZ model
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AXINO IN SUSY

- **SUSY+PQ**

motivated by both gauge hierarchy and strong CP
Goldstone axion is supersymmetrized

$$a \quad \longrightarrow \quad A = \frac{1}{\sqrt{2}}(s + ia) + \sqrt{2}\theta\tilde{a} + \theta^2 F_A$$

- **Properties**

massless $\longrightarrow$ massive by SUSY breaking $m_{\tilde{a}} \sim m_{3/2}$

But in some models, $m_{\tilde{a}} \sim \mathcal{O}(\text{keV})$ Tamvakis, Wyler; Nieves; Goto,
Yamaguchi; Chun, Kim, Nilles;
Chun, Lukas

couplings: suppressed by PQ scale $\gtrsim 10^9 \text{ GeV}$

$\longrightarrow$ *Feebly Interacting Massive Particle*
or SuperWIMP

MODEL

- **SUSY DFSZ model**

$$W_{\text{DFSZ}} = \frac{y_0}{M_*} X^2 H_u H_d ,$$

~~PQ~~

$$X = \frac{v_{\text{PQ}}}{\sqrt{2}} e^{A/v_{\text{PQ}}} ,$$

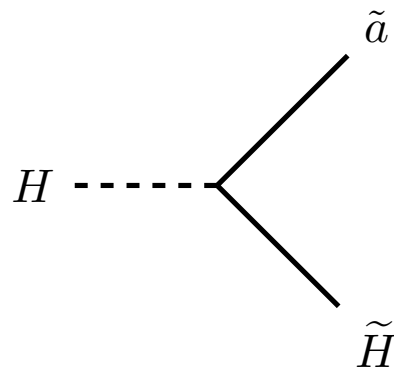
- generates **mu-term** $\mu \sim \frac{y_0 v_{\text{PQ}}^2}{2M_*}$

Kim, Nilles (1984)

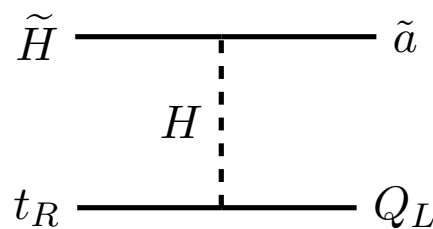
“effectively dimensionless”

- **axino interaction** $\frac{2\mu}{v_{\text{PQ}}} A H_u H_d$ $\frac{\mu}{v_{\text{PQ}}} \sim 10^{-8}$

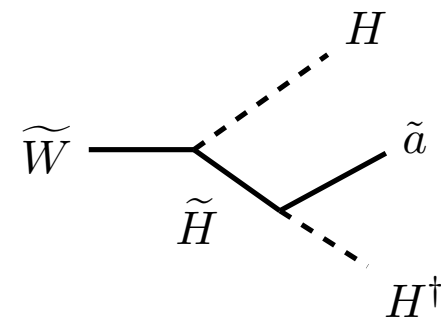
“Freeze-in” production [Hall, Jedamzik, March-Russell, West \(2009\)](#)



2-body decay



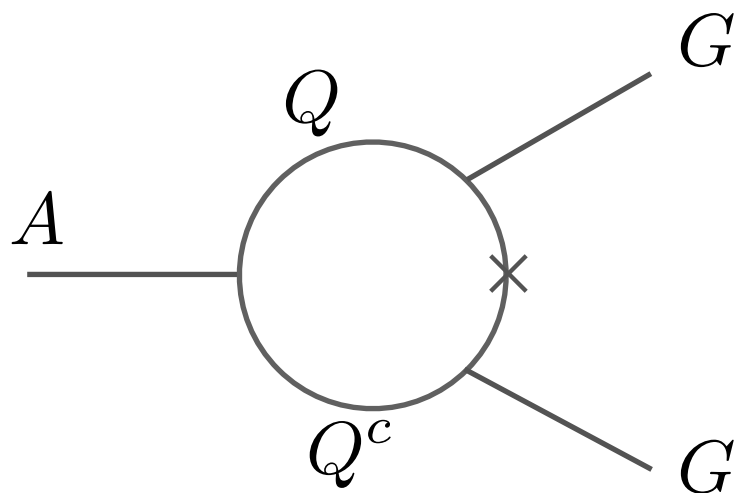
2-to-2



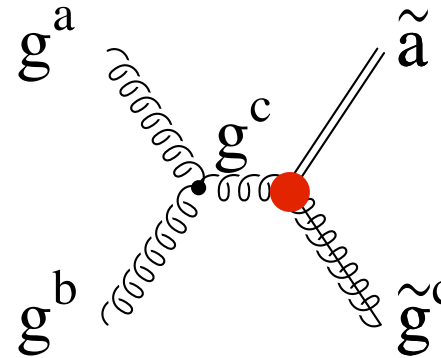
3-body decay

UV PRODUCTION?

- ElectroWeak Symmetry Breaking & SM quark loops



$$\sim \frac{g_s^2}{32\pi^2} \frac{1}{F_a} \bar{a} \gamma_5 \sigma^{\mu\nu} \tilde{g}^a \partial_\mu G_\nu^a$$



- 1PI amplitude: suppressed $\mathcal{A}_{1\text{PI}} \propto \frac{m_Q^2}{E^2}$ KJB, Choi, Im (2011)

- Above the weak scale (or before EW phase transition),
UV production is negligible.

R-PARITY VIOLATION

- PQ charge $Q_{\text{PQ}} \{X, H_u, H_d, L_i\} = \{-1, 1, 1, 2\}$

Chun (1999); Choi, Chun, Hwang (2001); Chun, Kim (2006)

$$W_{\text{bRPV}} = \frac{y'_i}{M_*^2} X^3 L_i H_u \simeq \mu'_i \left(1 + \frac{3A}{v_{\text{PQ}}} \right) L_i H_u,$$

- Bilinear RPV induces **axino-neutrino mixing**

$$|\theta| \simeq \frac{\mu' v_u}{m_{\tilde{a}} v_{\text{PQ}}} \simeq 10^{-5} \left(\frac{\mu'}{4 \text{ MeV}} \right) \left(\frac{7 \text{ keV}}{m_{\tilde{a}}} \right) \left(\frac{10^{10} \text{ GeV}}{v_{\text{PQ}}} \right)$$

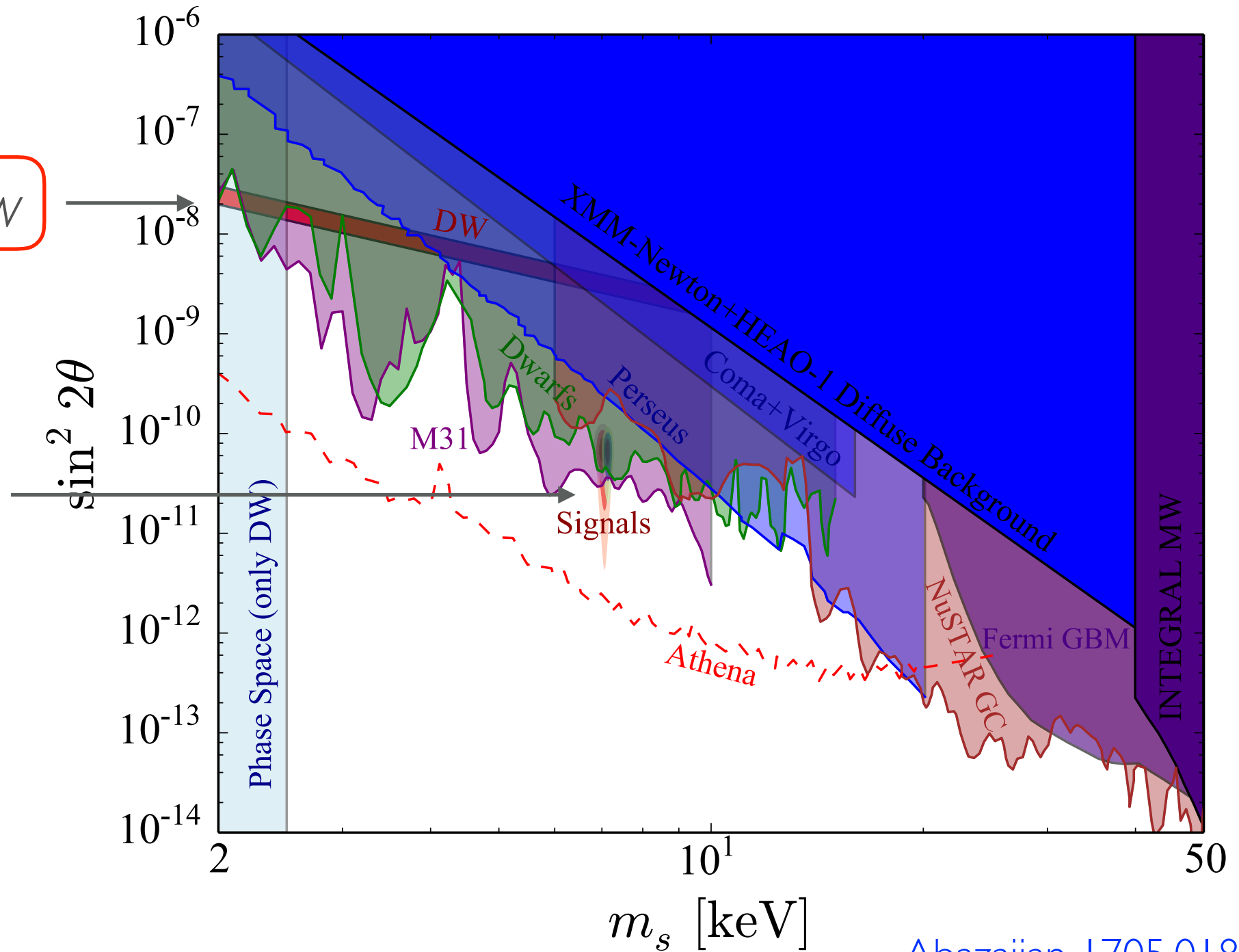
- **Axino as a sterile neutrino**

- decays into neutrino & *photon*
- can be produced via Dodelson-Widrow mechanism

STERILE NEUTRINO

Dodelson-Widrow

X-ray line



Abazajian 1705.01837

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BOLTZMANN EQ.

- Boltzmann eq. for phase space distribution

$$\frac{df_{\tilde{a}}(t, p)}{dt} = \frac{\partial f_{\tilde{a}}(t, p)}{\partial t} - \frac{\dot{a}(t)}{a(t)} p \frac{\partial f_{\tilde{a}}(t, p)}{\partial p} = \frac{1}{E_{\tilde{a}}} C(t, p)$$

$f_{\tilde{a}}(t, p)$: phase space distribution

$a(t)$: cosmic scale factor

$E_{\tilde{a}}$: axino energy $C(t, p)$: collision term

- Negligible $f_{\tilde{a}}(t, p)$ in the collision term

$$f_{\tilde{a}}(t_f, p) = \int_{t_i}^{t_f} dt \frac{1}{E_{\tilde{a}}} C \left(t, \frac{a(t_f)}{a(t)} p \right)$$

collision terms determine distribution

PRODUCTION PROCESSES

- Relevant production processes of axinos

2-body decay: e.g. $\tilde{H} \rightarrow H + \tilde{a}$

3-body decay: e.g. $\tilde{W} \rightarrow H + H + \tilde{a}$

2-to-2 scattering: e.g. $\tilde{H} + t \rightarrow t + \tilde{a}$

- **Freeze-in nature**

all relevant processes occur **near threshold scale**

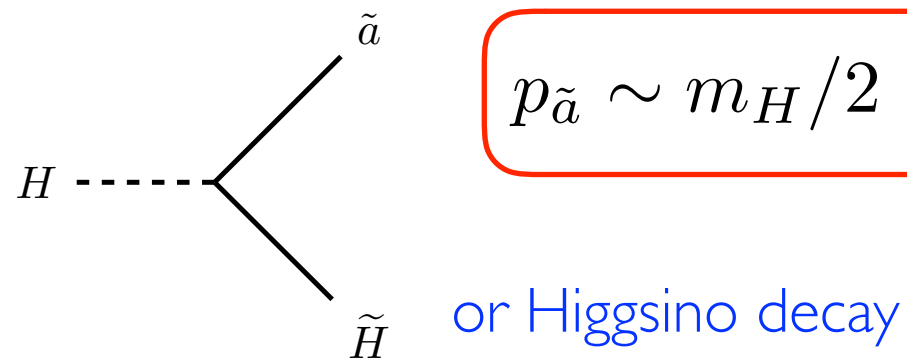
e.g. $\sim \mu$ -term scale for Higgsino decay

➔ $T \sim \mu > T_c$

axino production *before electroweak phase transition*

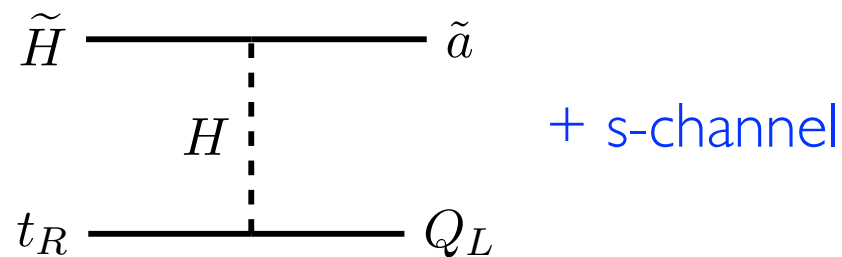
COLLISION TERMS

- 2-body decay



$$p_{\tilde{a}} \sim m_H/2 \quad \text{vs.} \quad T \sim m_H$$

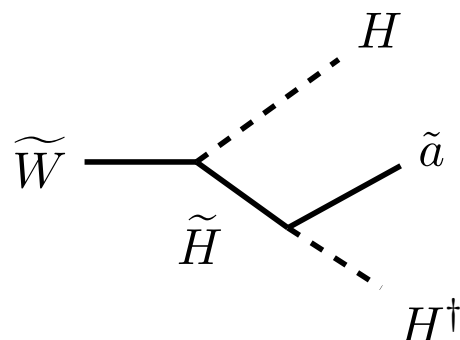
- 2-to-2 scattering



$$p_{\tilde{a}} \sim \sqrt{s} \quad \text{vs.} \quad T \sim \sqrt{s}$$

different dists. for s- and t-channel

- 3-body decay

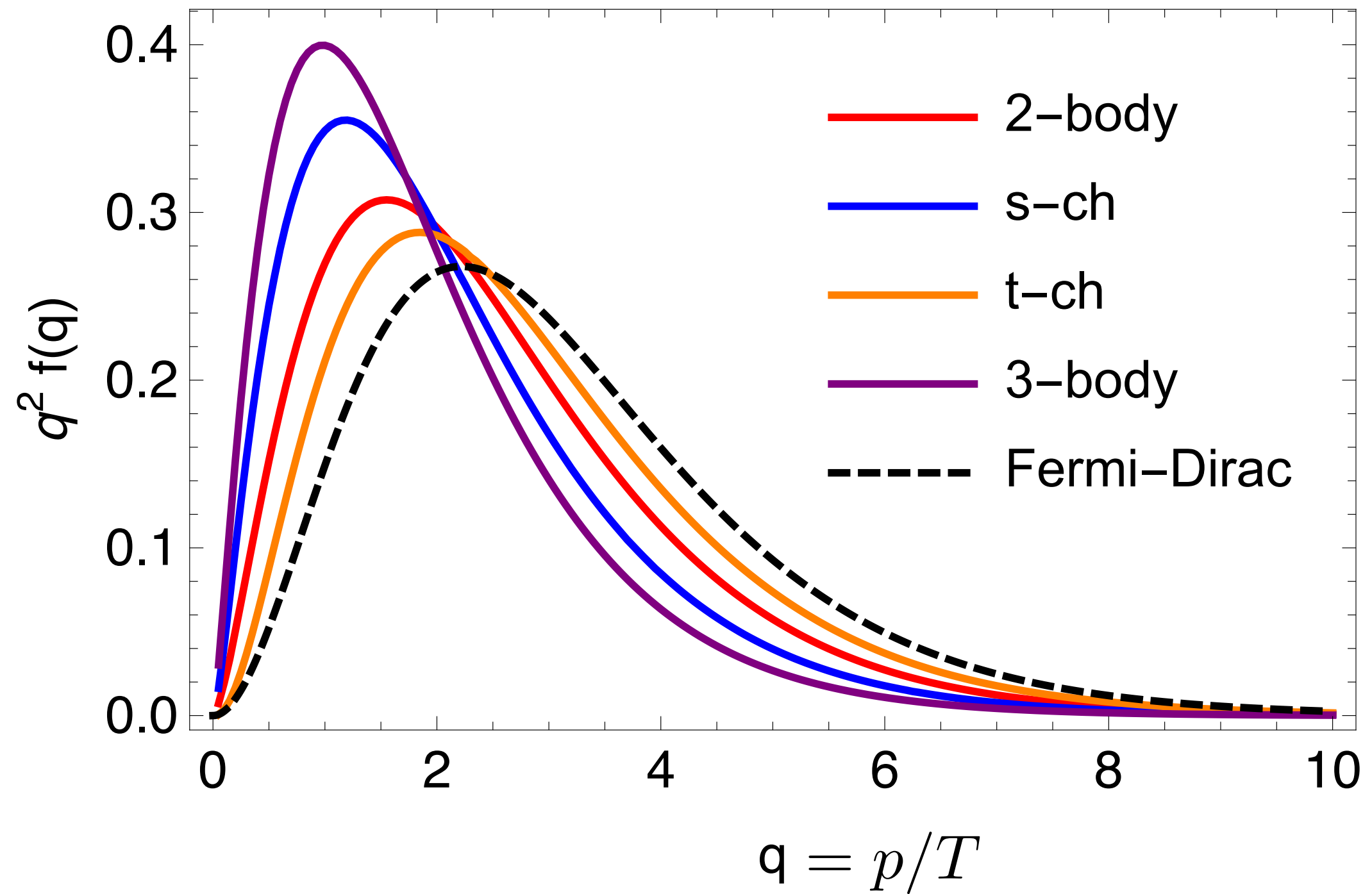


$$p_{\tilde{a}} \sim m_{\widetilde{W}}/3 \quad \text{vs.} \quad T \sim m_{\widetilde{W}}$$

comparable to scattering cross section

e.g. $\widetilde{W} + H \rightarrow H + \tilde{a}$

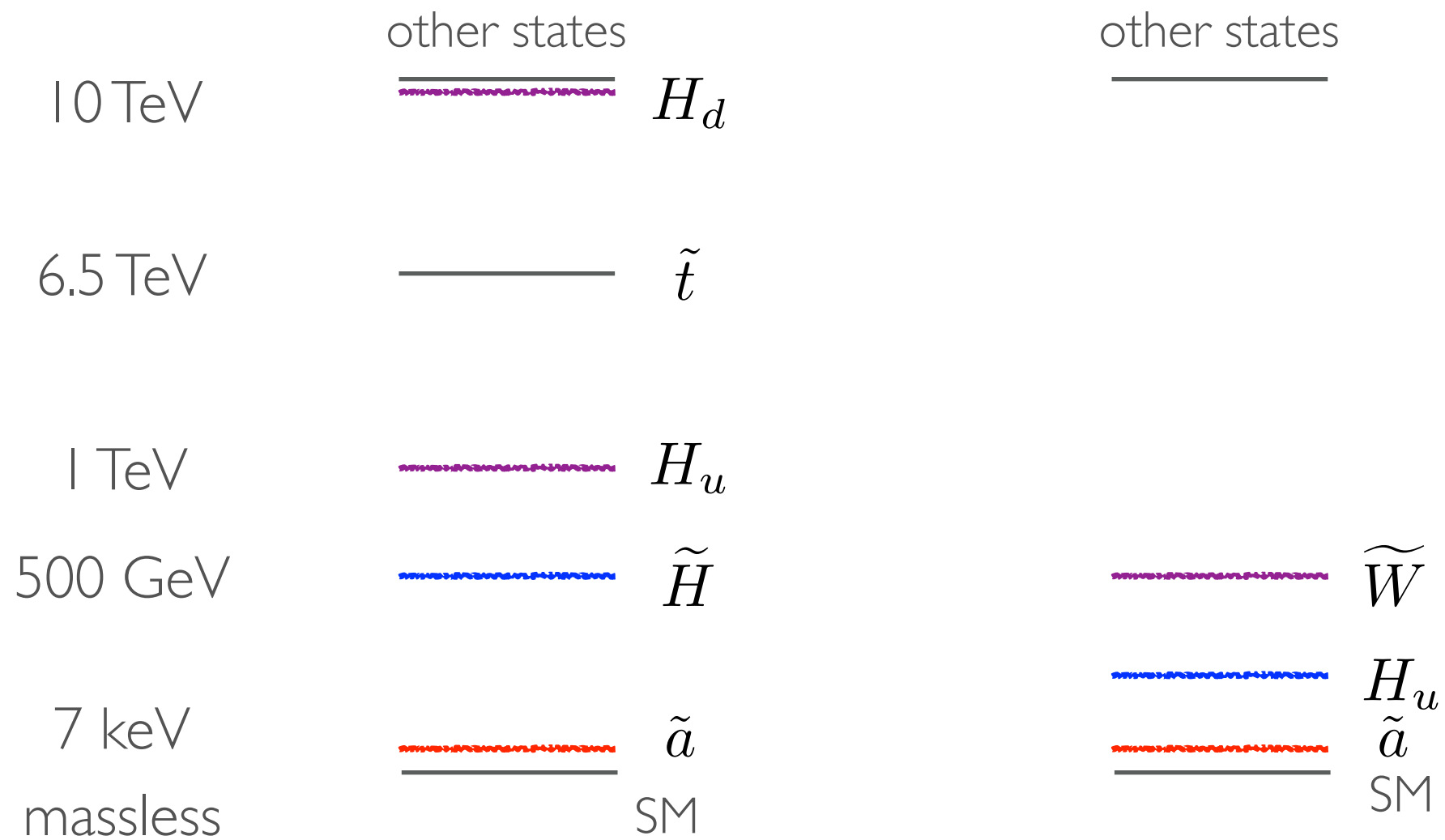
DISTRIBUTION



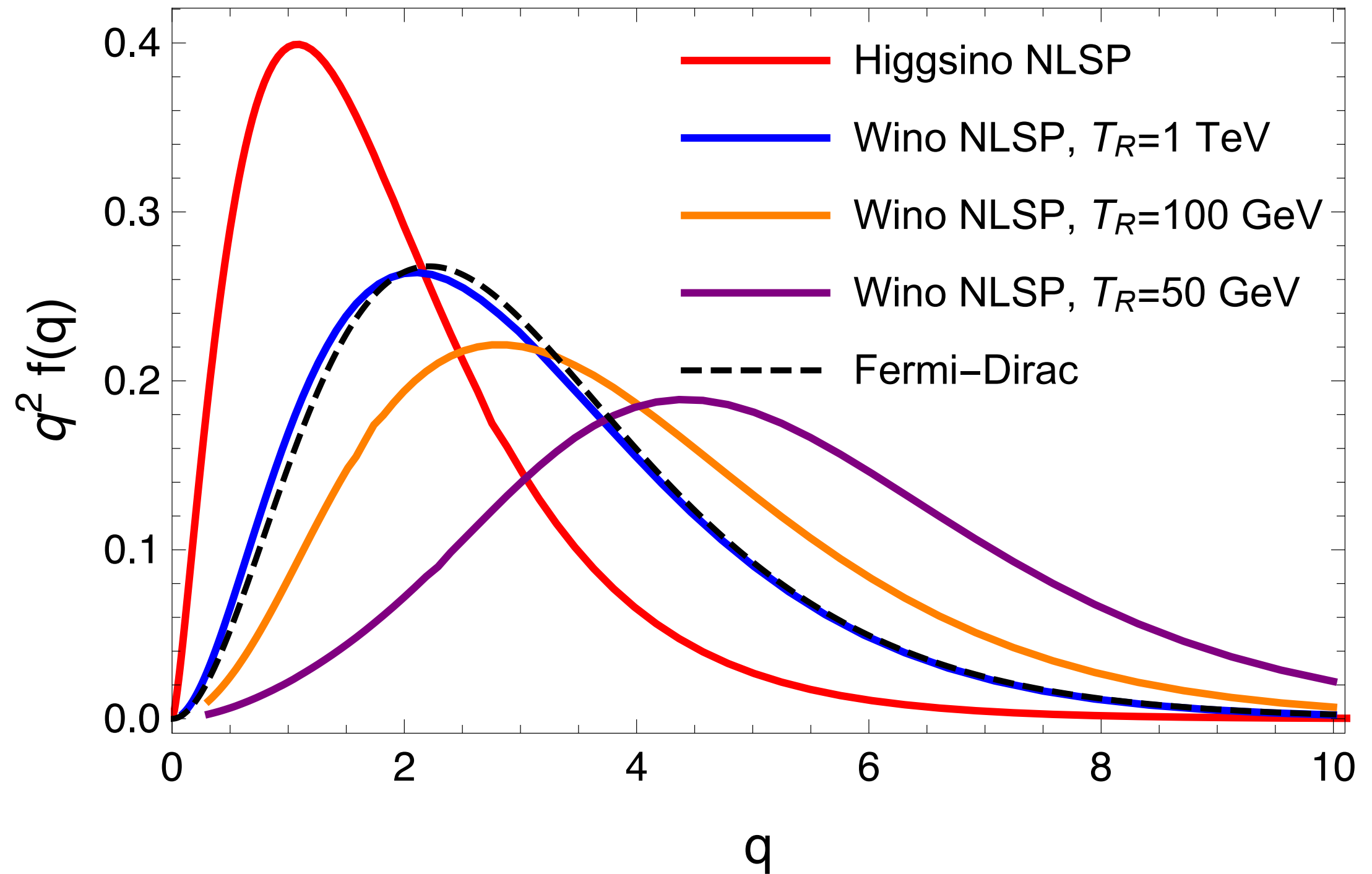
BENCHMARK SCENARIOS

BM1 (Higgsino NLSP)

BM2 (Wino NLSP)



DISTRIBUTION



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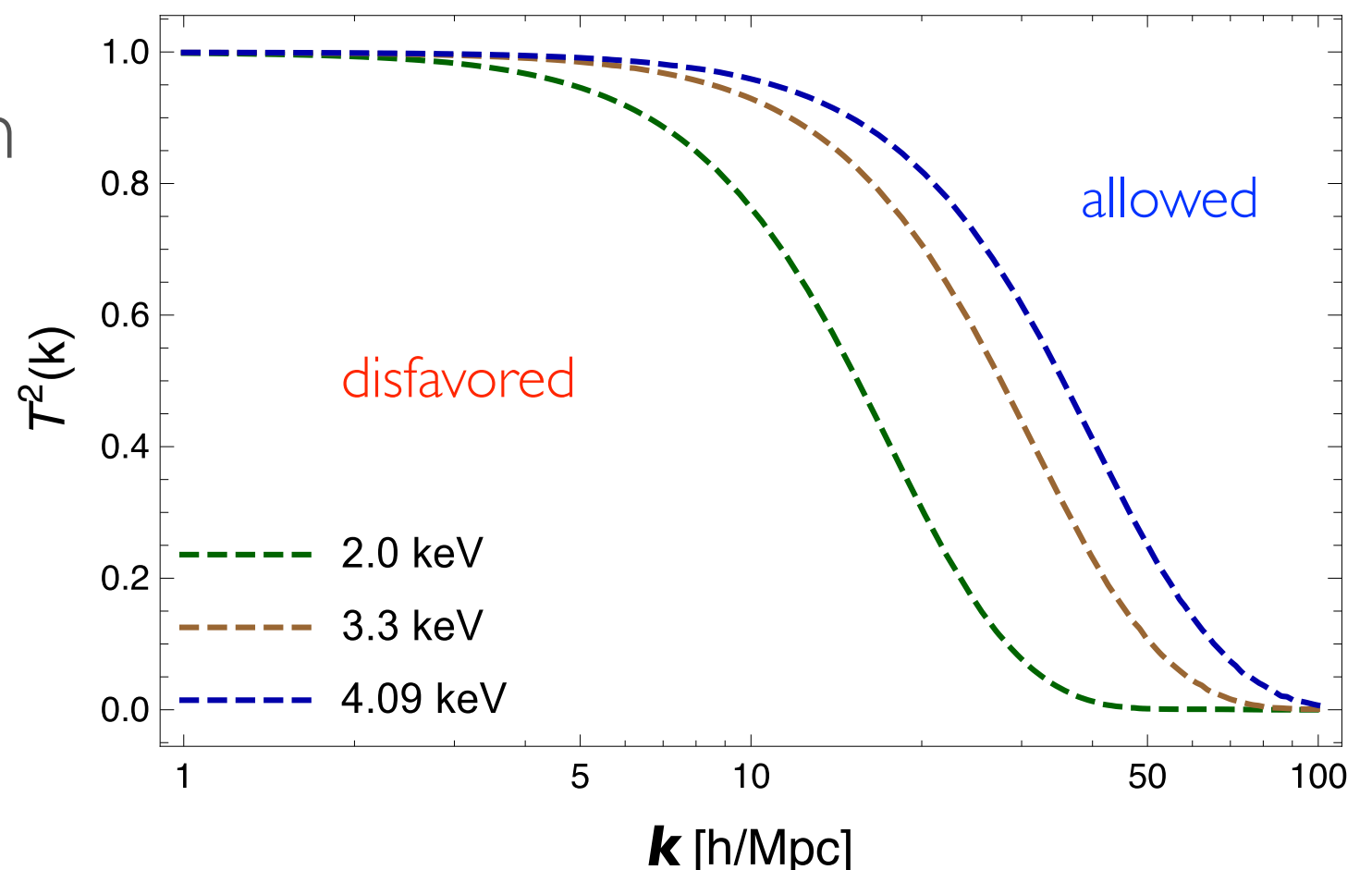
SQUARED TRANSFER FUNC.

- Ly-alpha bounds: assuming FD dist. and observed DM density
➔ constrain warm DM mass

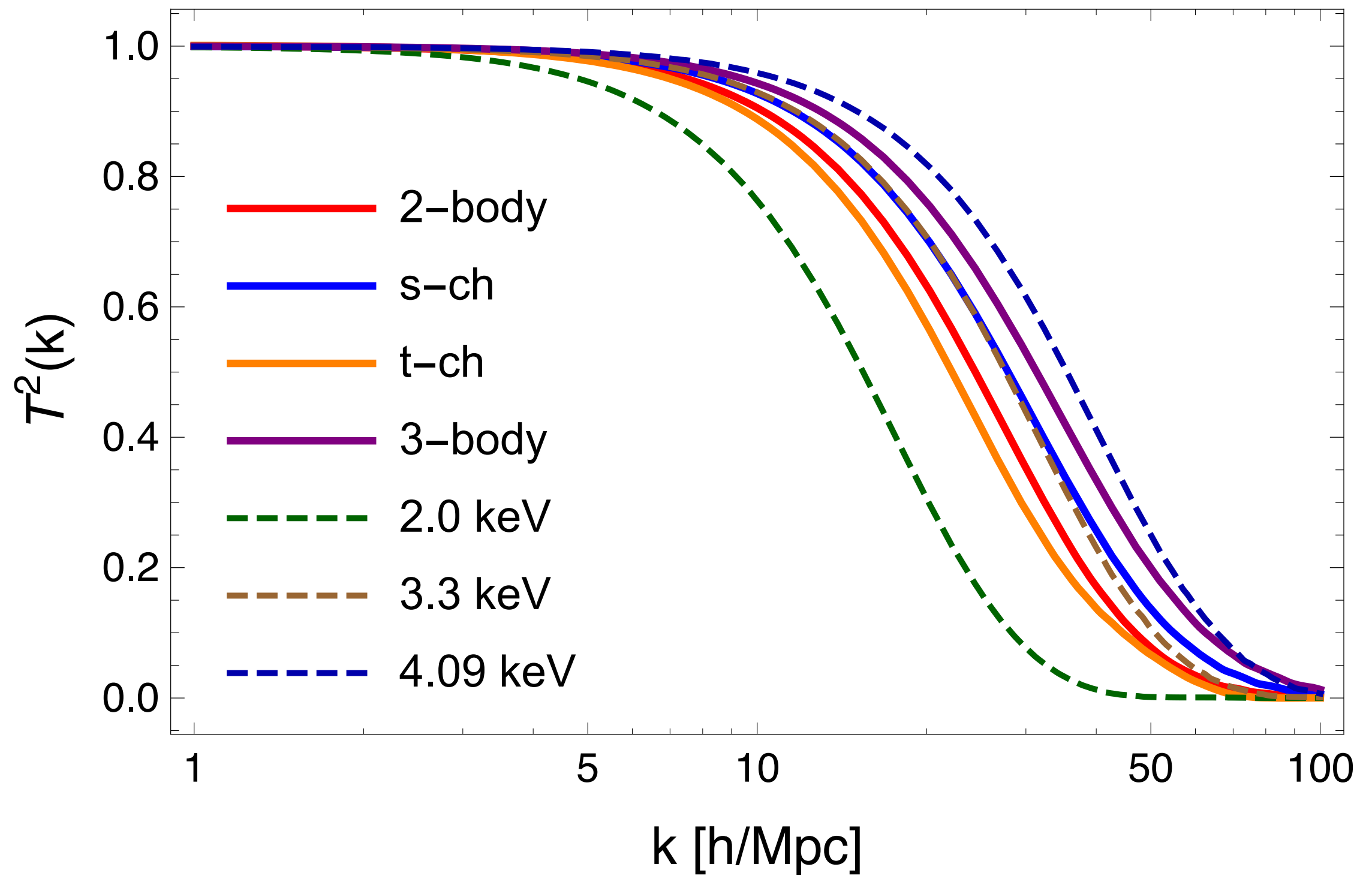
- Freeze-in Axino: non-FD dist.
➔ need *linear matter power spectrum* to compare it with Ly-alpha

- Squared Transfer Function

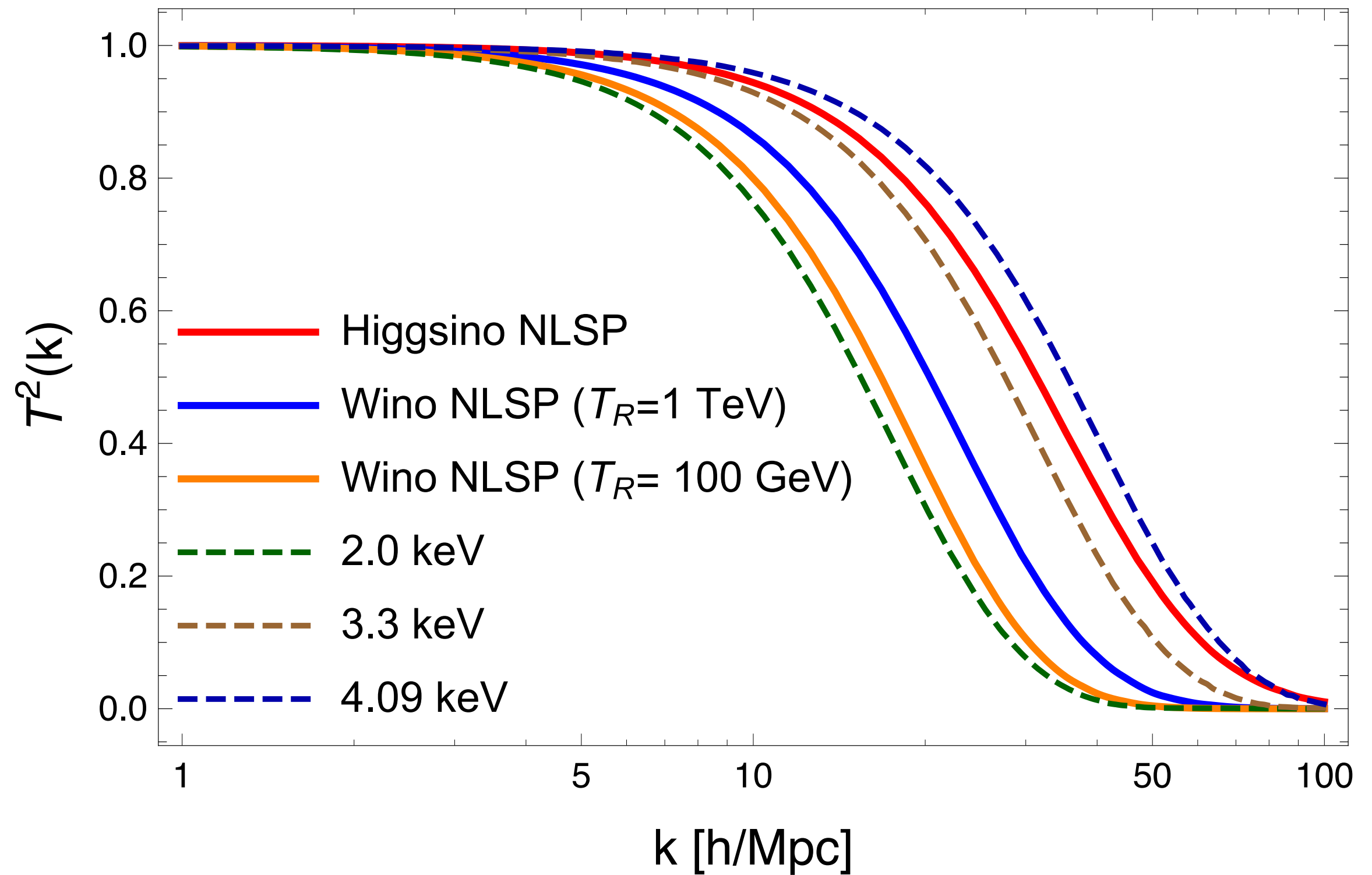
$$\mathcal{T}^2(k) = \frac{P(k)}{P_{\text{CDM}}(k)}$$



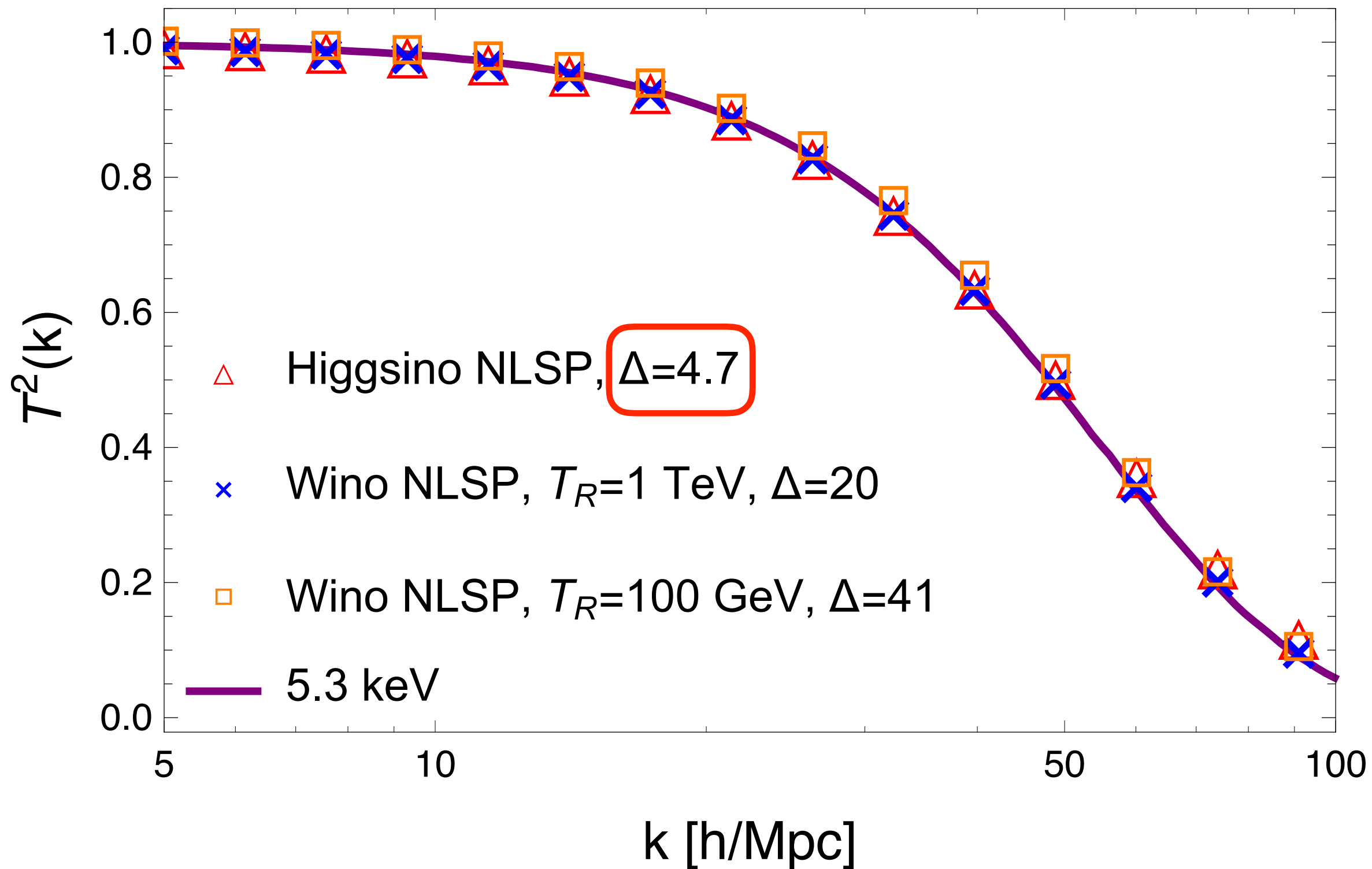
MATTER POWER SPECTRUM



MATTER POWER SPECTRUM



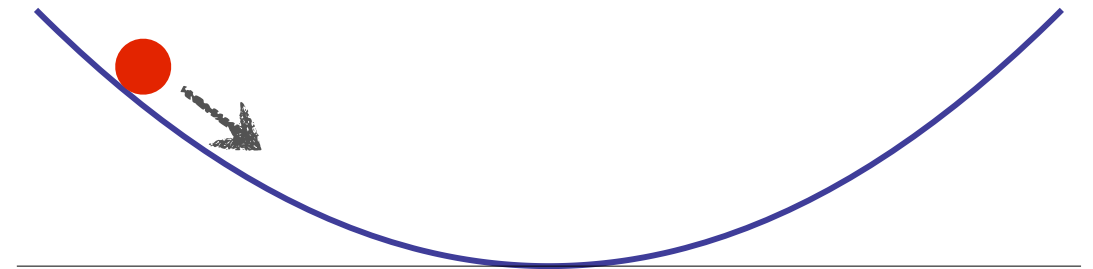
ENTROPY



SAXION DECAY

- Coherent oscillation of saxion:

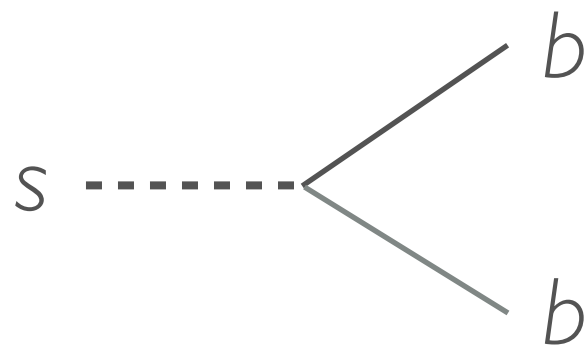
$$Y_s^{\text{CO}} \simeq 1.9 \times 10^{-6} \left(\frac{\text{GeV}}{m_s} \right) \left(\frac{\min[T_R, T_s]}{10^7 \text{ GeV}} \right) \left(\frac{s_0}{10^{12} \text{ GeV}} \right)^2$$



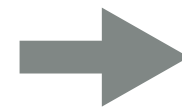
- Saxion dominated universe at

$$T_e^s = \frac{4}{3} m_s Y_s^{\text{CO}} \simeq 2.5 \times 10^2 \text{ GeV} \left(\frac{\min[T_R, T_s]}{10^7 \text{ GeV}} \right) \left(\frac{s_0}{10^{16} \text{ GeV}} \right)^2$$

- Saxion decay



$$\begin{aligned} v_{\text{PQ}} &= 2.5 \times 10^{10} \text{ GeV} \\ m_s &\simeq 110 \text{ GeV} \\ T_D^s &\simeq 53 \text{ GeV} \end{aligned}$$



$$\Delta = \frac{T_e^s}{T_D^s} \simeq 4.7$$

RELIC ABUNDANCE

- **Higgsino NLSP (BM1) case**

By integrating $q^2 f_{\tilde{a}}(q)$

$$\Omega_{\tilde{a}} h^2 \simeq 0.1 \left(\frac{4.7}{\Delta} \right) \left(\frac{2.5 \times 10^{10} \text{ GeV}}{v_{\text{PQ}}} \right) \left(\frac{m_{\tilde{a}}}{7 \text{ keV}} \right)$$

Axinos can be the dominant DM.

- **Wino NLSP case (BM2)**

hard to get enough entropy due to low T_R

For large T_R , it becomes similar to Higgsino NLSP.

CONCLUSIONS

- Axino can be DM when its mass is $\sim \text{keV}$.
- Under R-parity violation, its decay signal can be observed: 3.5 keV X-ray excess?
- SUSY DFSZ model accommodates both μ -term for freeze-in production and bilinear RPV for axino decay.
- While 7 keV DM with FD dist. has tension with Ly-alpha $m_{\text{WDM}} > 3.3 \text{ keV}$, freeze-in axino can be consistent with $m_{\text{WDM}} > 5.3 \text{ keV}$ with mild entropy dilution.
- Saxion ($m = 110 \text{ GeV}$) decay can make mild dilution.
- Axino can explain the observed DM density.