LIGHT AXINOS:
DECAY, FREEZE-IN PRODUCTION & LYMAN-ALPHA CONSTRAINTS

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based on
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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?*

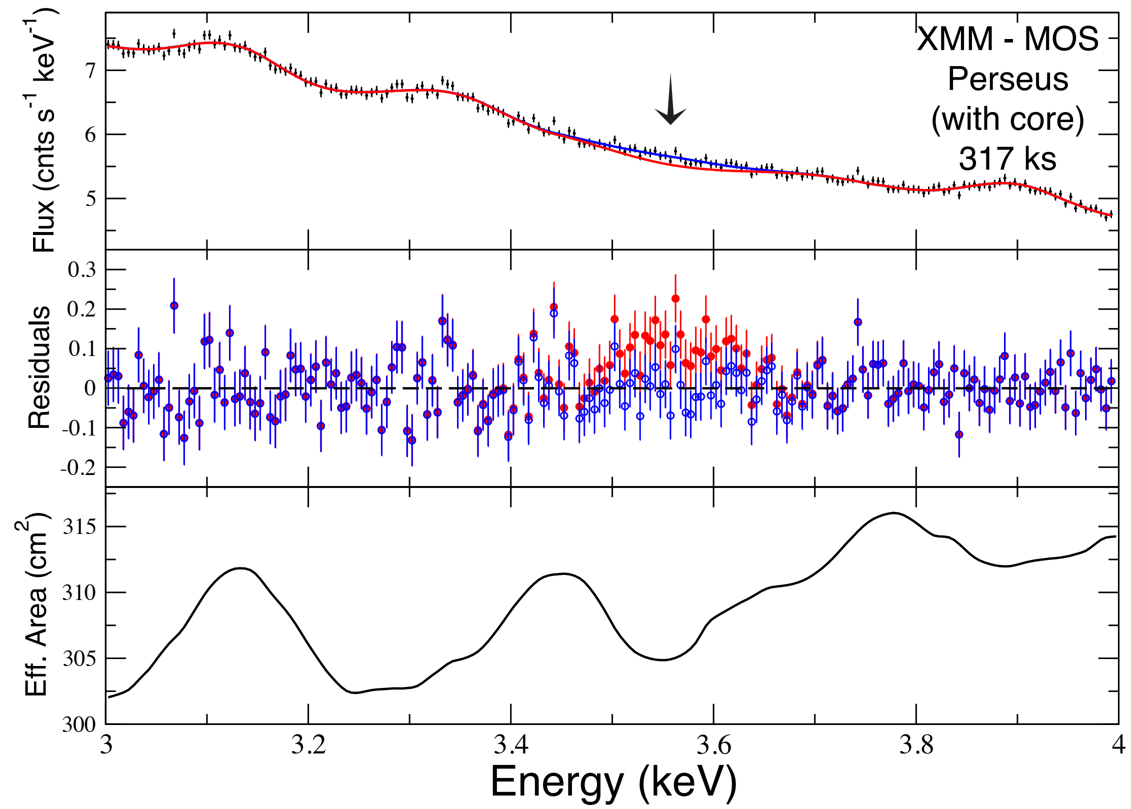
  - affects *matter power spectrum?*

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

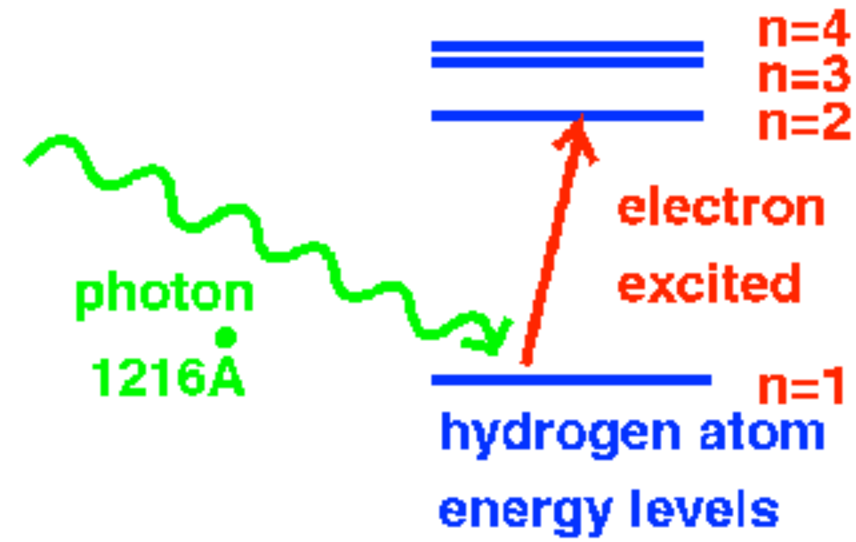
  see Profumo's slides.

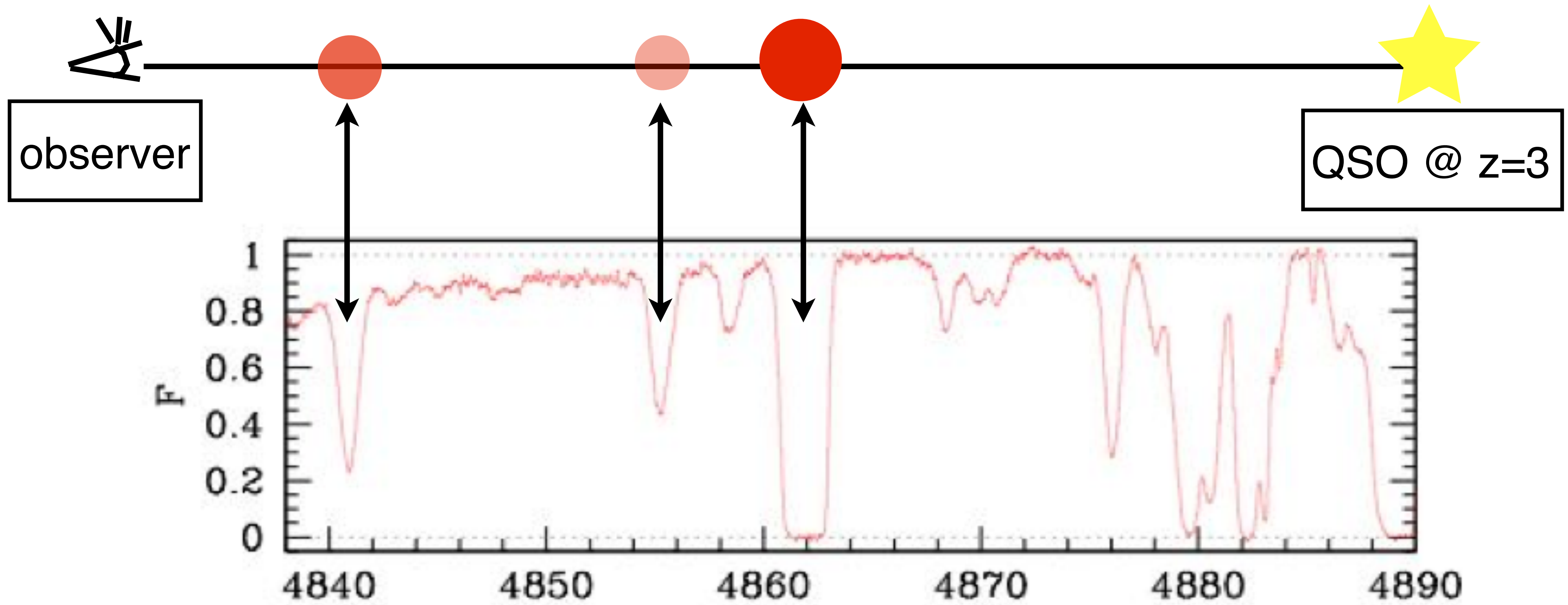
- In this study,

  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





slide by A. Kamada

LYMAN-ALPHA FOREST

- Improving constraints on "warm dark matter mass"

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

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

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

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

- ***Warm Dark Matter***

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

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

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

➡ need *linear matter power spectrum*

LYMAN-ALPHA FOREST

- Improving constraints on "warm dark matter mass"

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

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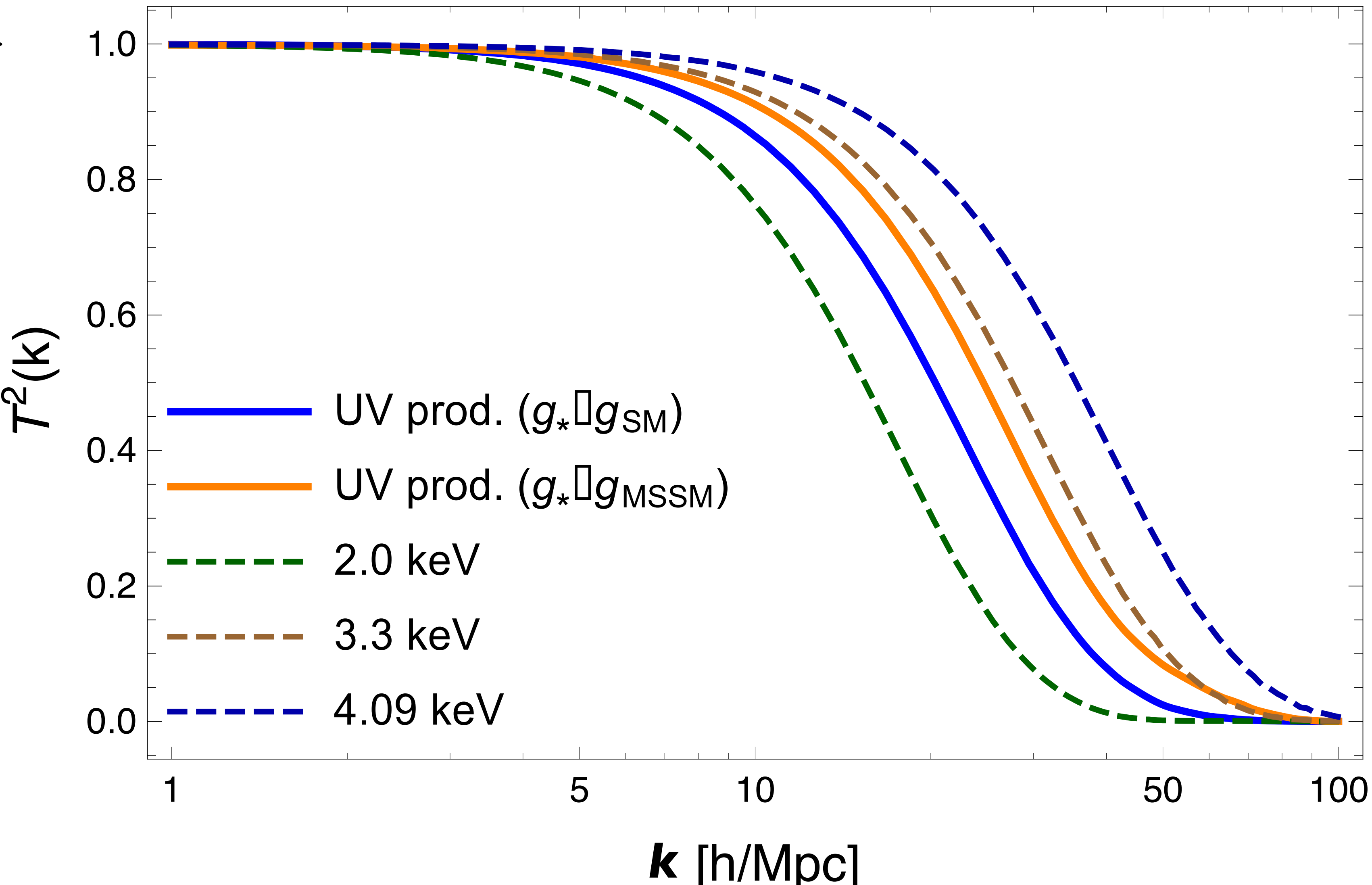

- ***Warm***

Ly-alpha ... observed

DM den

$\Omega_{\rm W}$ ... $)$

$g_*^{\rm WDM} \sim 70$ ...

➡ need *linear matter power spectrum*

OUTLINE

1. Introduction
2. SUSY DFSZ model
3. Freeze-in Axinos
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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 ➡ massive by SUSY breaking $m_{\tilde{a}} \sim m_{3/2}$

But in some models, $\boxed{m_{\tilde{a}} \sim \mathcal{O}(\mathrm{keV})}$

Tamvakis, Wyler; Nieves; Goto, Yamaguchi; Chun, Kim, Nilles; Chun, Lukas

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

➡ *Feebly Interacting Massive Particle*

or SuperWIMP

see Mambrini's slides.

MODEL

- ***SUSY DFSZ model***

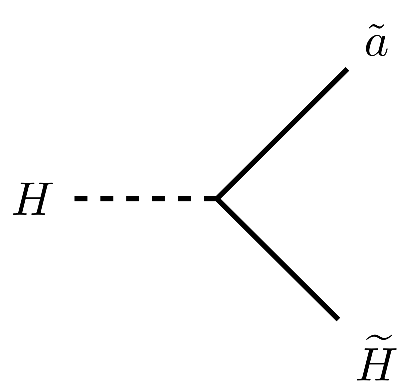
$$\boxed{W_{\rm DFSZ} = \frac{y_0}{M_*} X^2 H_u H_d\,,} \qquad \cancel{\rm PQ} \qquad X = \frac{v_{\rm PQ}}{\sqrt{2}} e^{A/v_{\rm PQ}}\,,$$

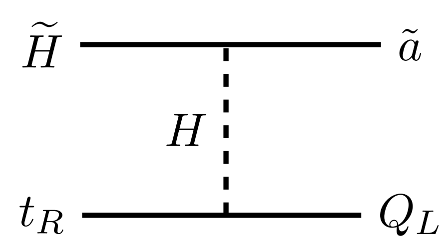
- generates **mu-term** $\quad \mu \sim \dfrac{y_0 v_{\rm PQ}^2}{2M_*}$ Kim, Nilles (1984)

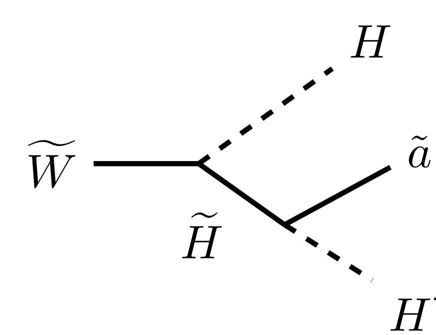
"effectively dimensionless"

- **axino interaction** $\quad \dfrac{2\mu}{v_{\rm PQ}} A H_u H_d \qquad \dfrac{\mu}{v_{\rm PQ}} \sim 10^{-8}$

"***Freeze-in***" production Hall, Jedamzik, March-Russell, West (2009)



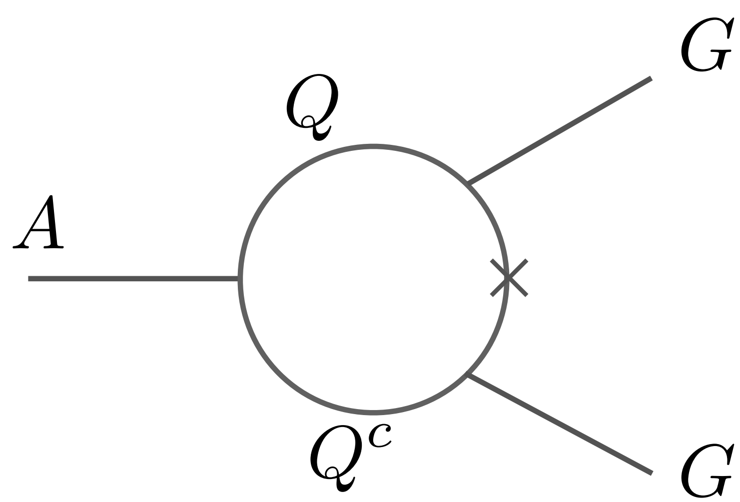




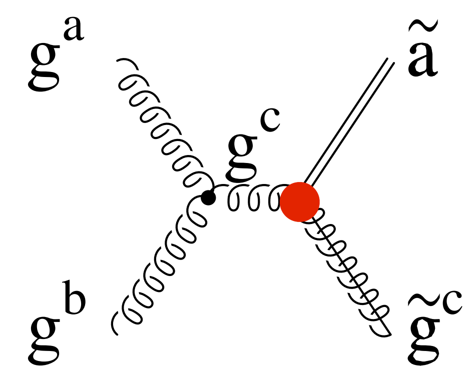
2-body decay 2-to-2 3-body decay

UV PRODUCTION?

- ElectroWeak Symmetry Breaking & SM quark loops



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



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

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

R-PARITY VIOLATION

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

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

$$\boxed{W_{\rm bRPV} = \frac{y_i'}{M_*^2} X^3 L_i H_u \simeq \mu_i' \left(1 + \frac{3A}{v_{\rm PQ}}\right) L_i H_u,}$$

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

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

- ***Axino as a sterile neutrino***

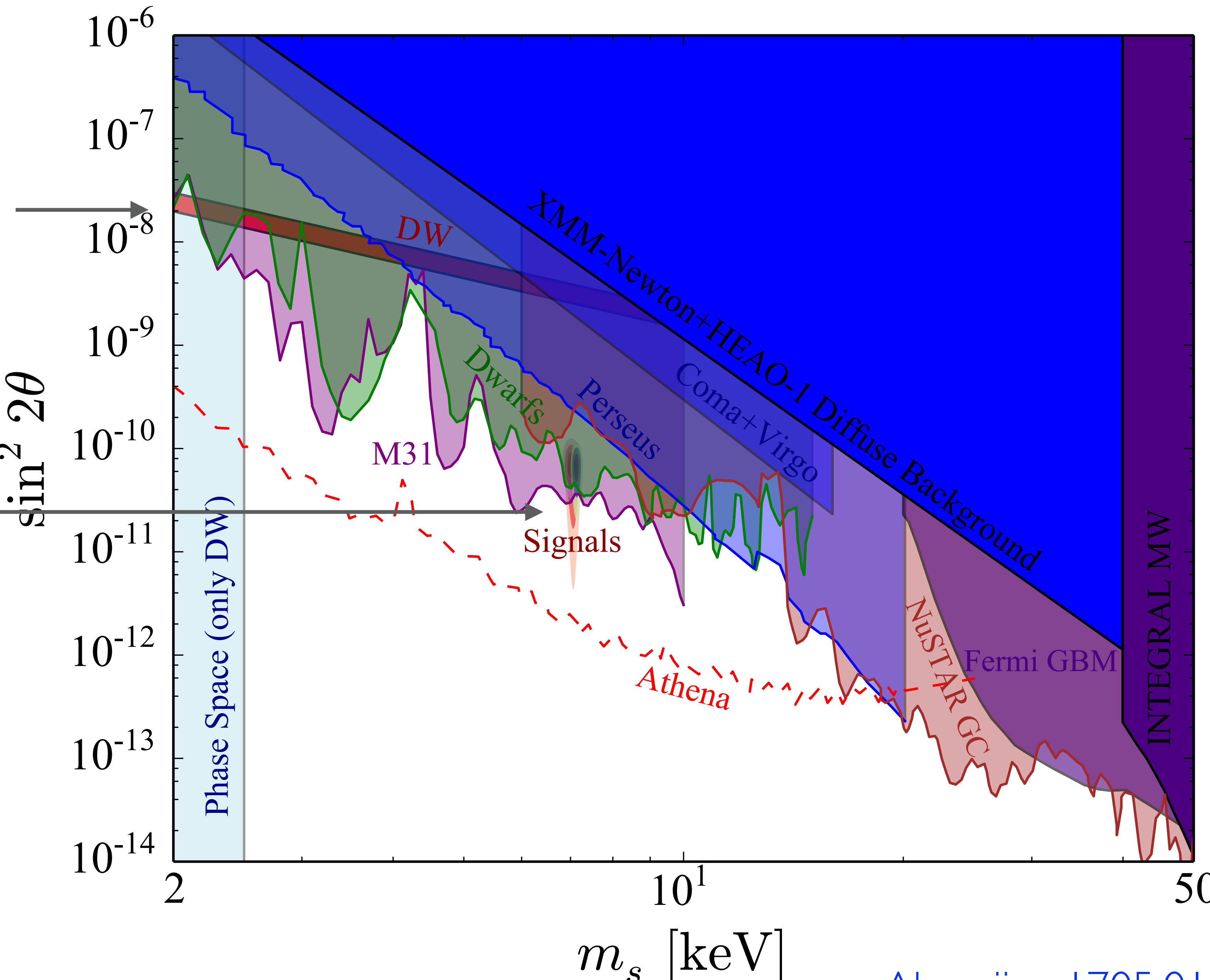
  - decays into neutrino & *photon*

  - 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. $\widetilde{H} \to H + \tilde{a}$

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

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

- ***Freeze-in nature***

  all relevant processes occur ***near threshold scale***

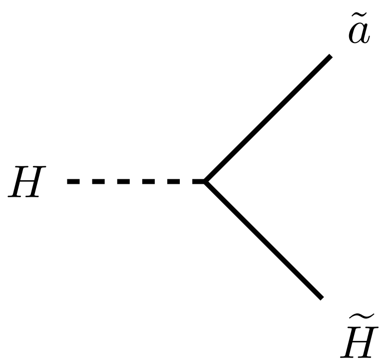
  e.g. ~mu-term scale for Higgsino decay

$$\Rightarrow \quad T \sim \mu > T_c$$

axino production *before electroweak phase transition*

COLLISION TERMS

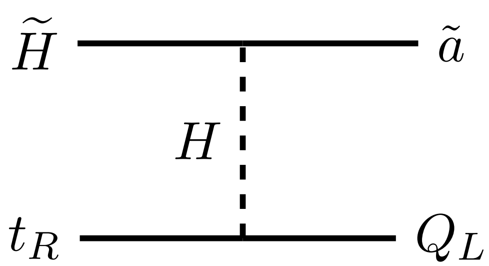
- 2-body decay



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

or Higgsino decay

- 2-to-2 scattering

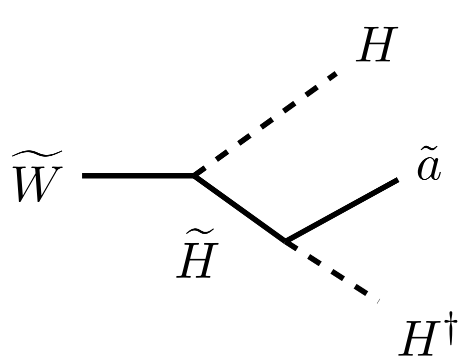


+ s-channel

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

different dists. for s- and t-channel

- 3-body decay

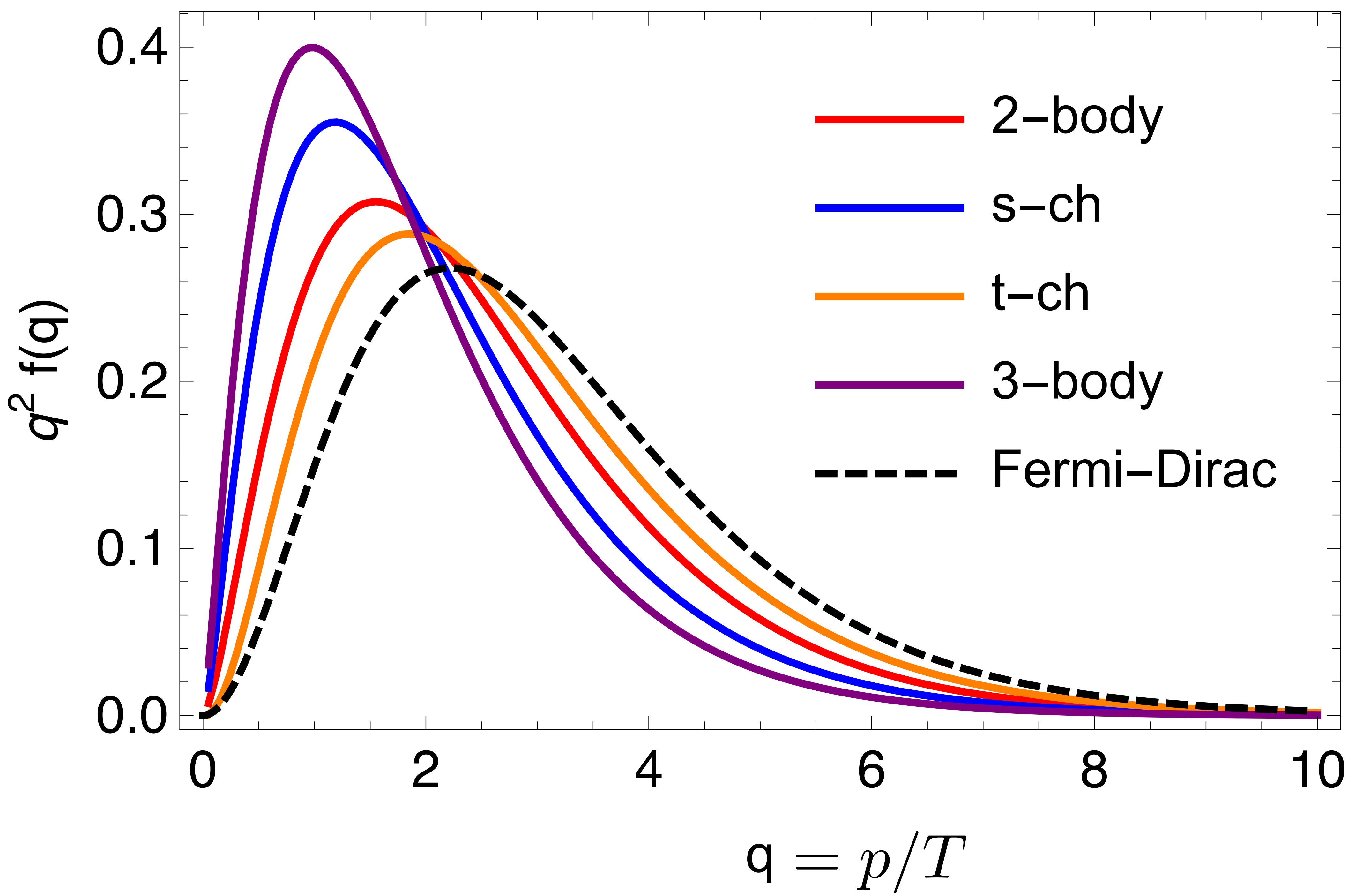


$$\boxed{p_{\tilde{a}} \sim m_{\widetilde{W}}/3 \qquad \text{vs.} \qquad T \sim m_{\widetilde{W}}}$$

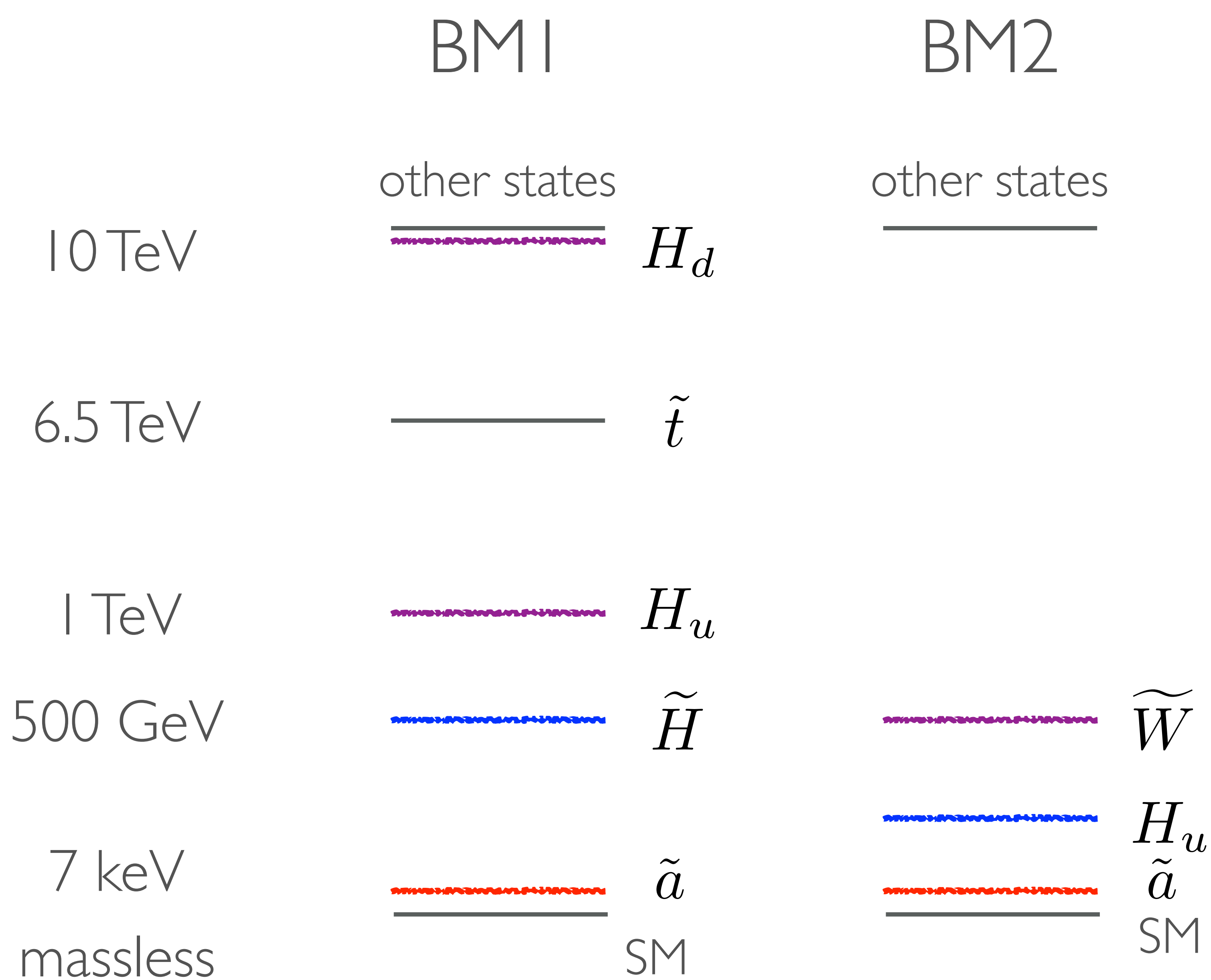
comparable to scattering cross section

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

DISTRIBUTION



BENCHMARK SCENARIOS



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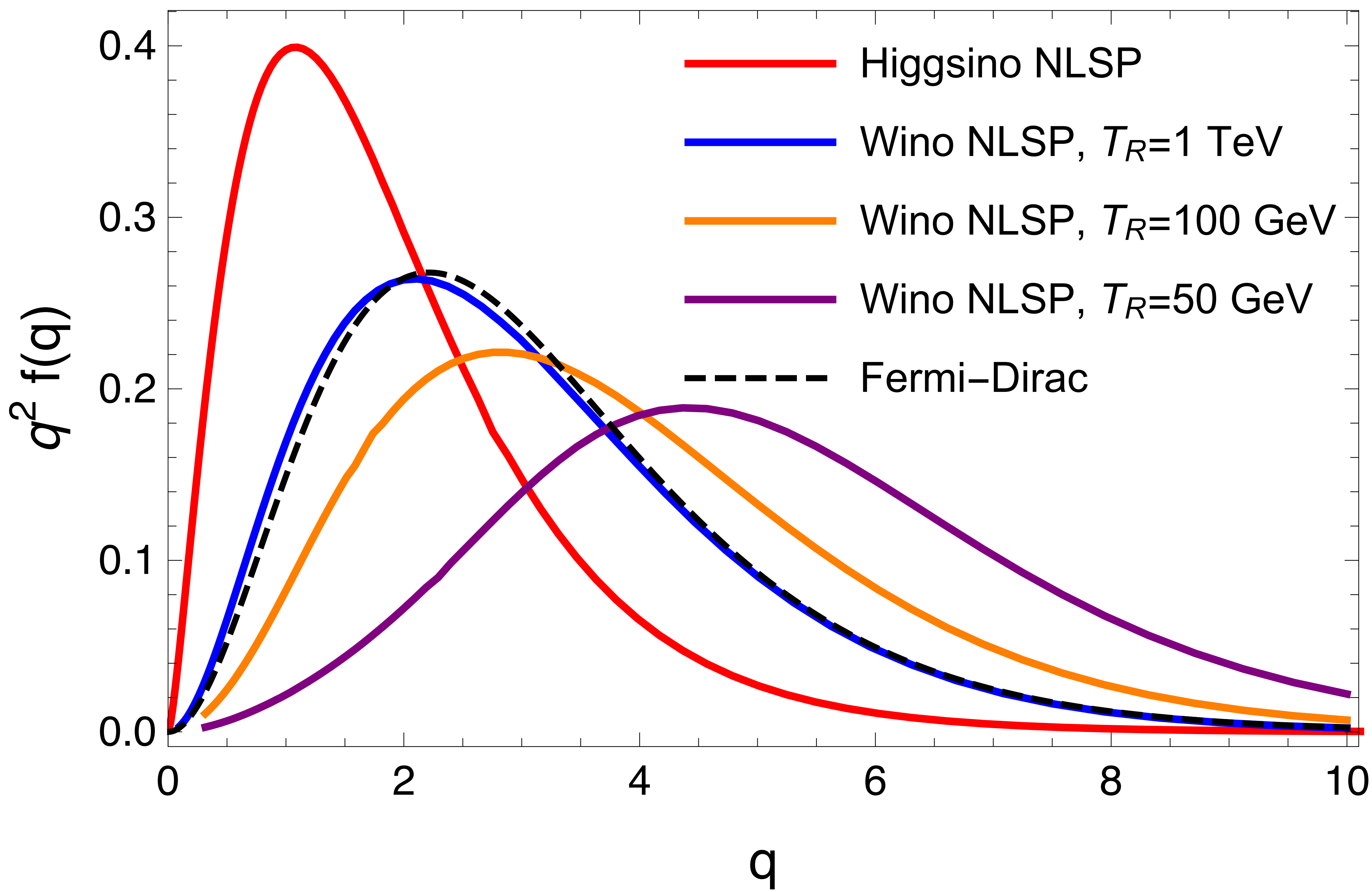

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SQUARED TRANSFER FUNC.

- Ly-alpha bounds: assuming FD dist. and observed DM density

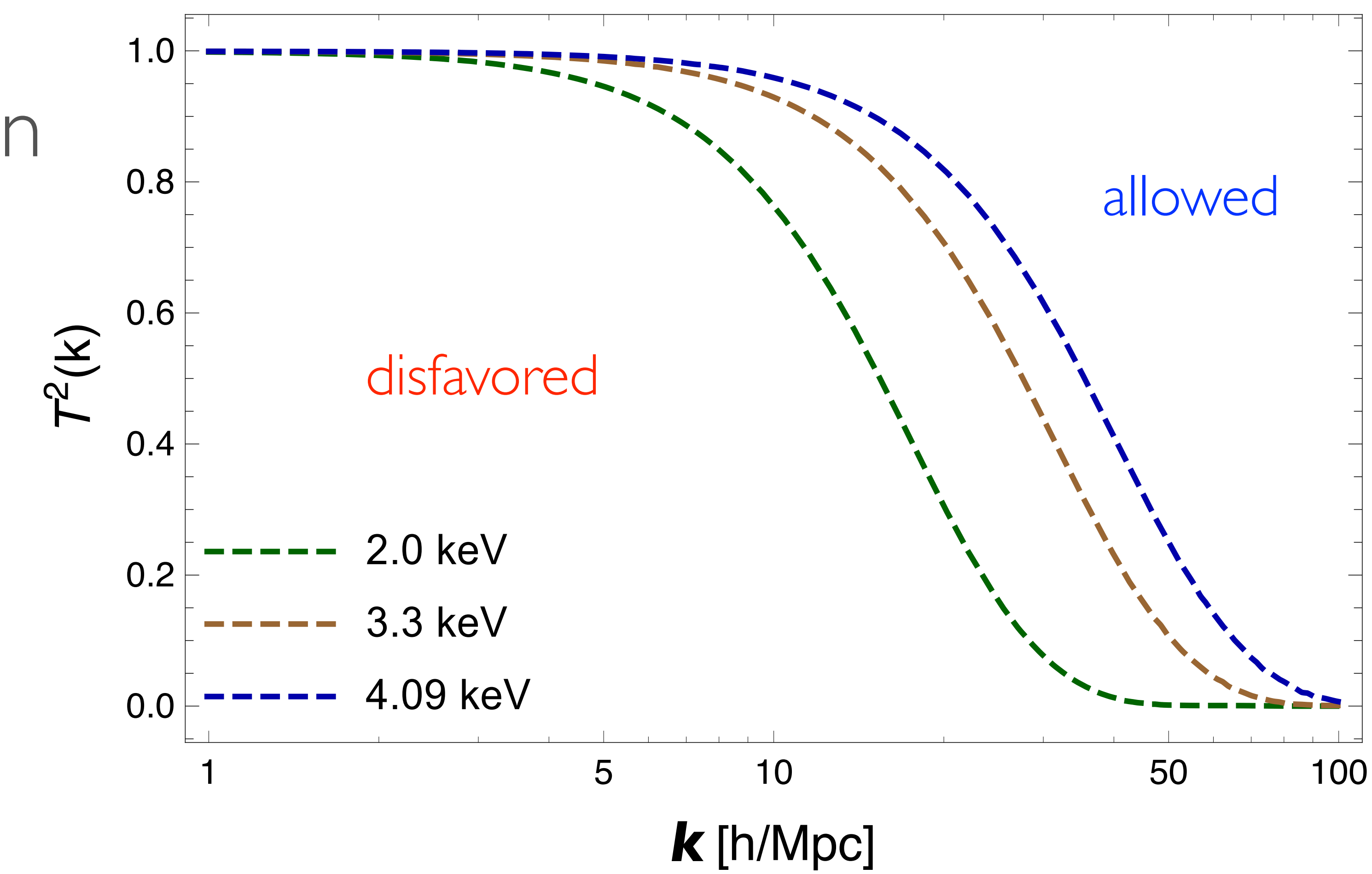
  ➡ constrain warm DM mass

- Freeze-in Axino: non-FD dist.

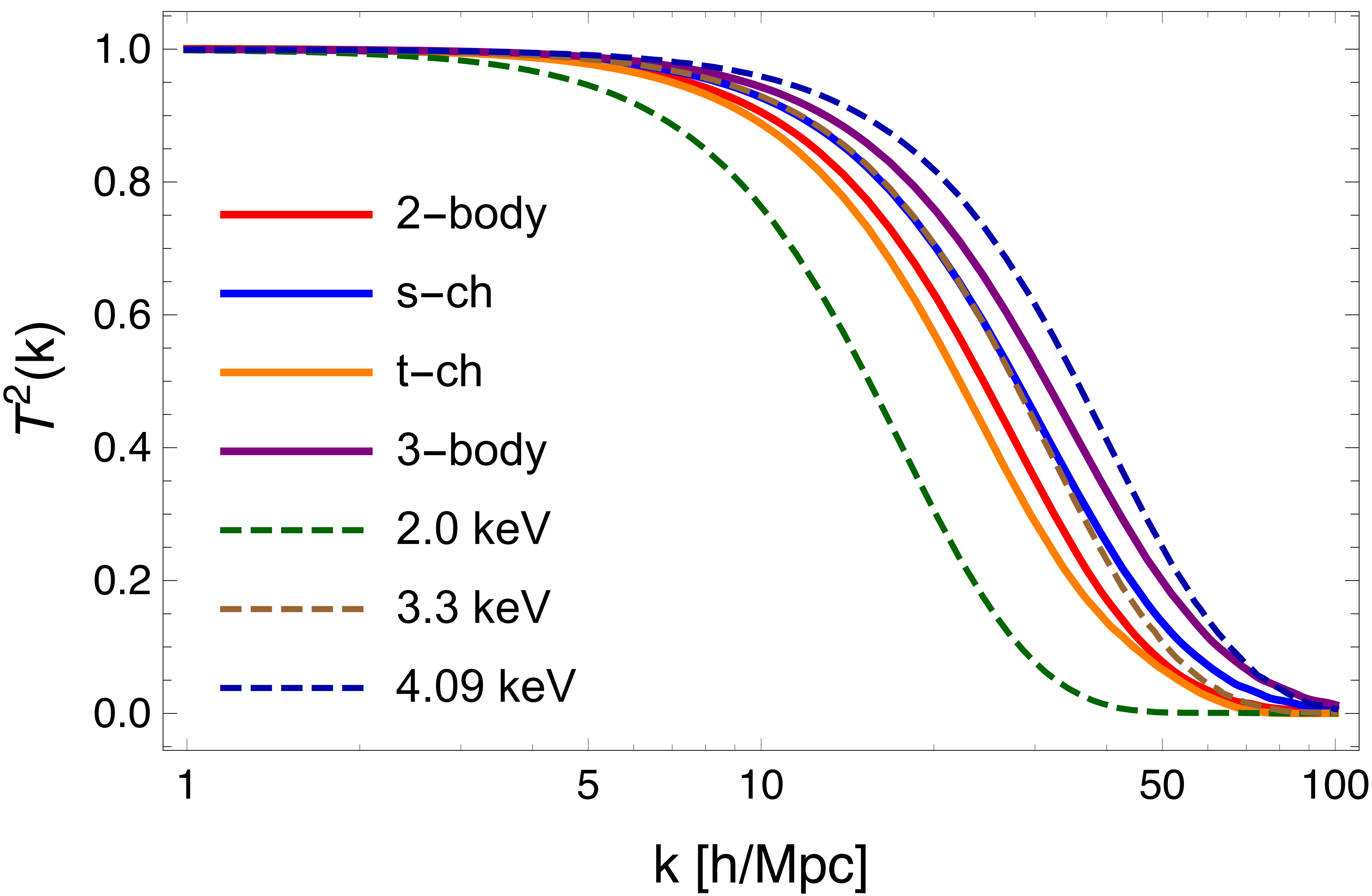
  ➡ need *linear matter power spectrum* to compare it with Ly-alpha

- Squared Transfer Function

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



MATTER POWER SPECTRUM



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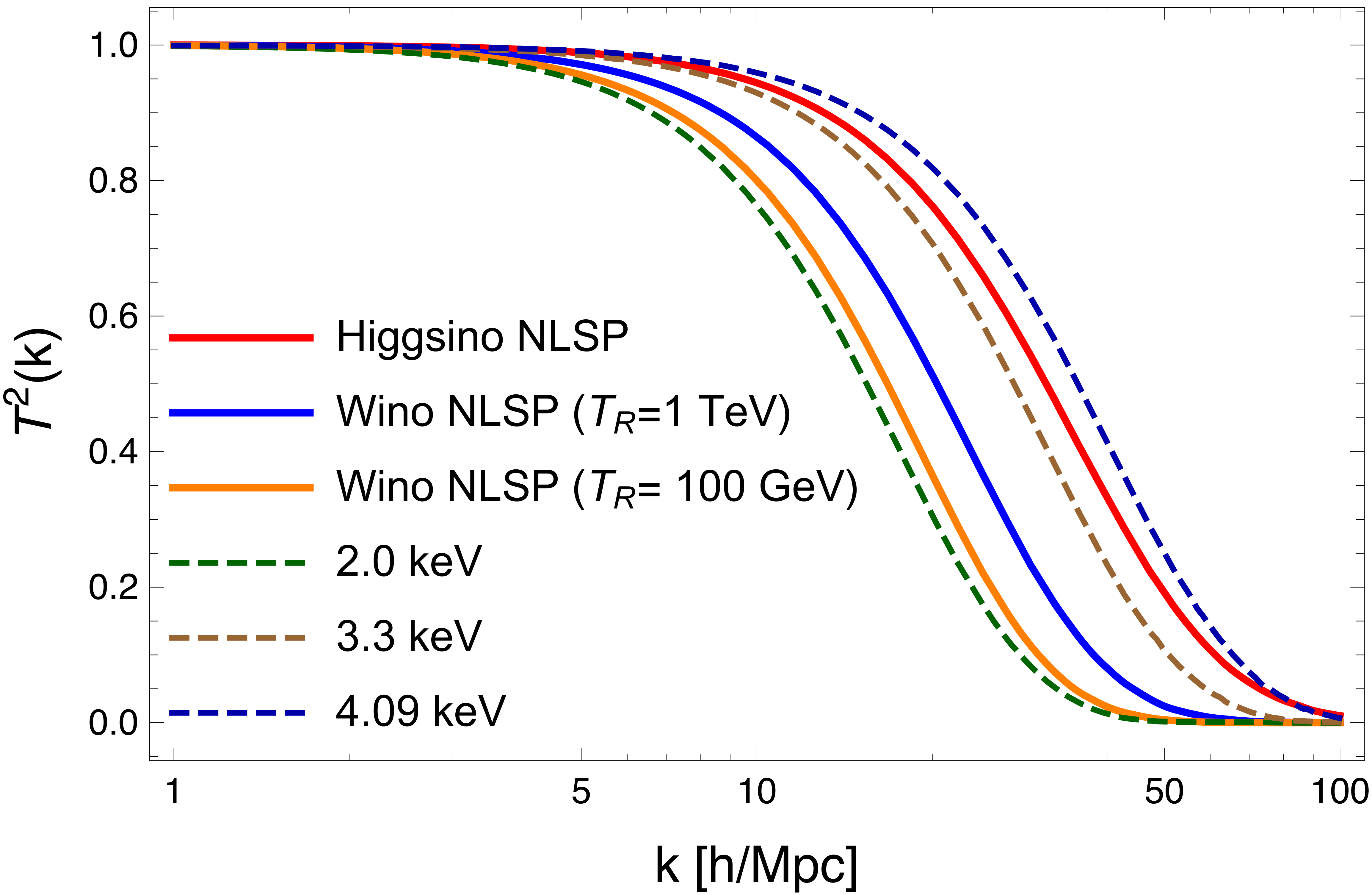
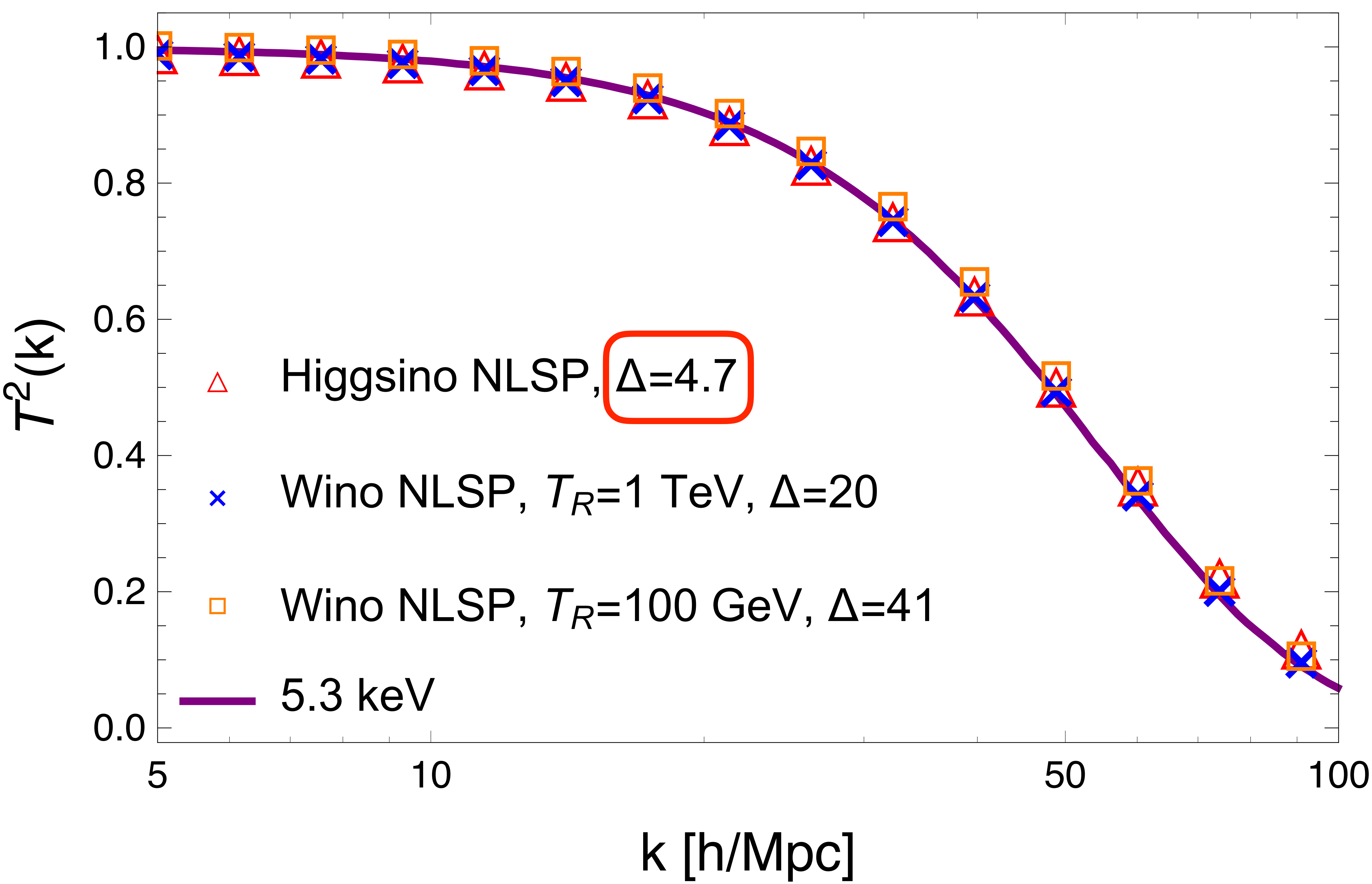


ENTROPY

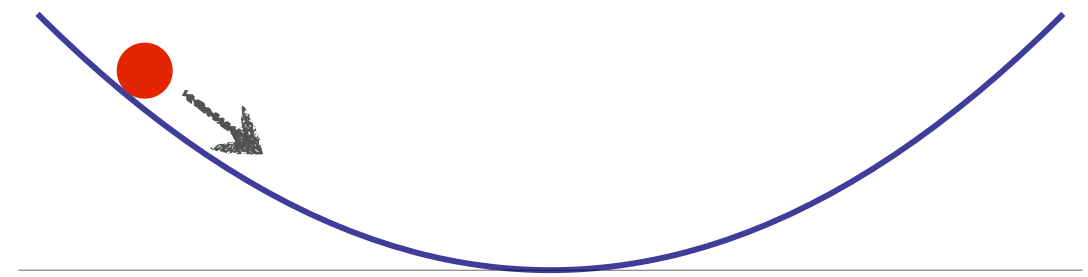


1.0
0.8
0.6
0.4
0.2
0.0
$T^2(k)$
Higgsino NLSP, Δ=4.7
Wino NLSP, T_R=1 TeV, Δ=20
Wino NLSP, T_R=100 GeV, Δ=41
5.3 keV
5
10
50
100
k [h/Mpc]

SAXION DECAY

- Coherent oscillation of saxion:

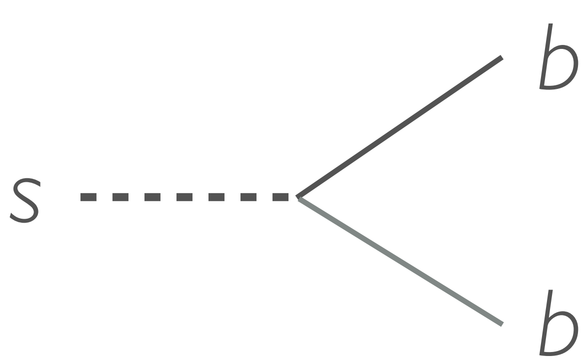
$$Y_s^{\rm CO} \simeq 1.9\times 10^{-6}\left(\frac{\rm GeV}{m_s}\right)\left(\frac{\min[T_R,T_s]}{10^7\,{\rm GeV}}\right)\left(\frac{s_0}{10^{12}\,{\rm GeV}}\right)^2$$



- Saxion dominated universe at

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

- Saxion decay



$$v_{\rm PQ} = 2.5\times 10^{10}\ {\rm GeV}$$

$$m_s \simeq 110\ {\rm GeV}$$

$$T_D^s \simeq 53\ {\rm GeV}$$

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

RELIC ABUNDANCE

- ***Higgsino NLSP (BM1) case***

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

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

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