Constraints on 7 keV Freeze-in DM:

Phase Space Distributions & Ly-α forest constraints

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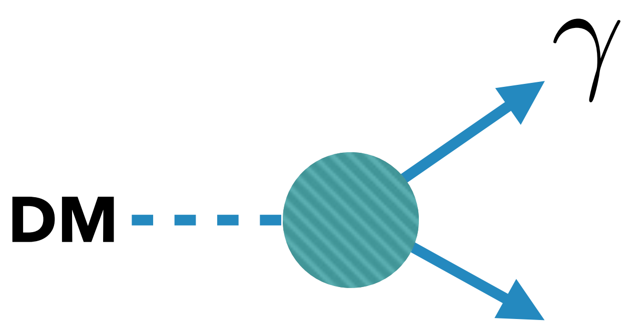
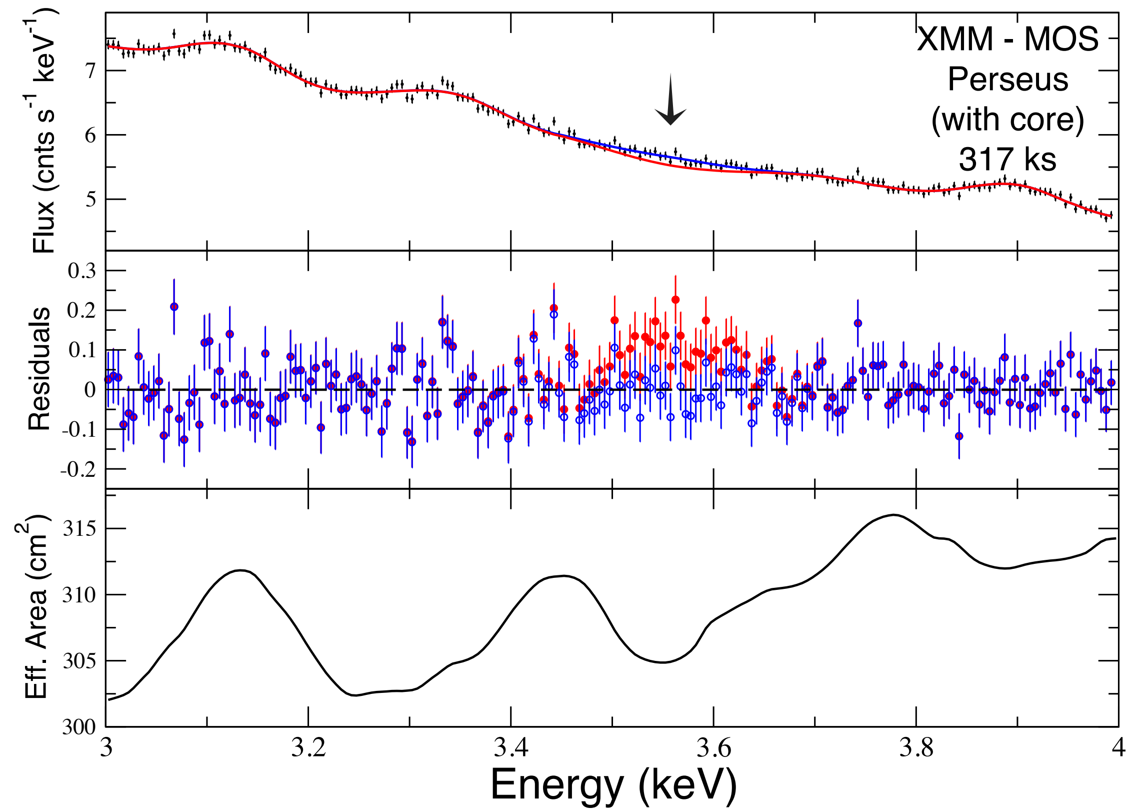
3.5 keV X-ray excess?

- Rare decay of 7 keV DM?
  From Perseus galaxy cluster, Andromeda galaxy…





- Criticism
  - K XVIII explanation ??
  - No signal from dSph, stacked galaxies and groups, M31

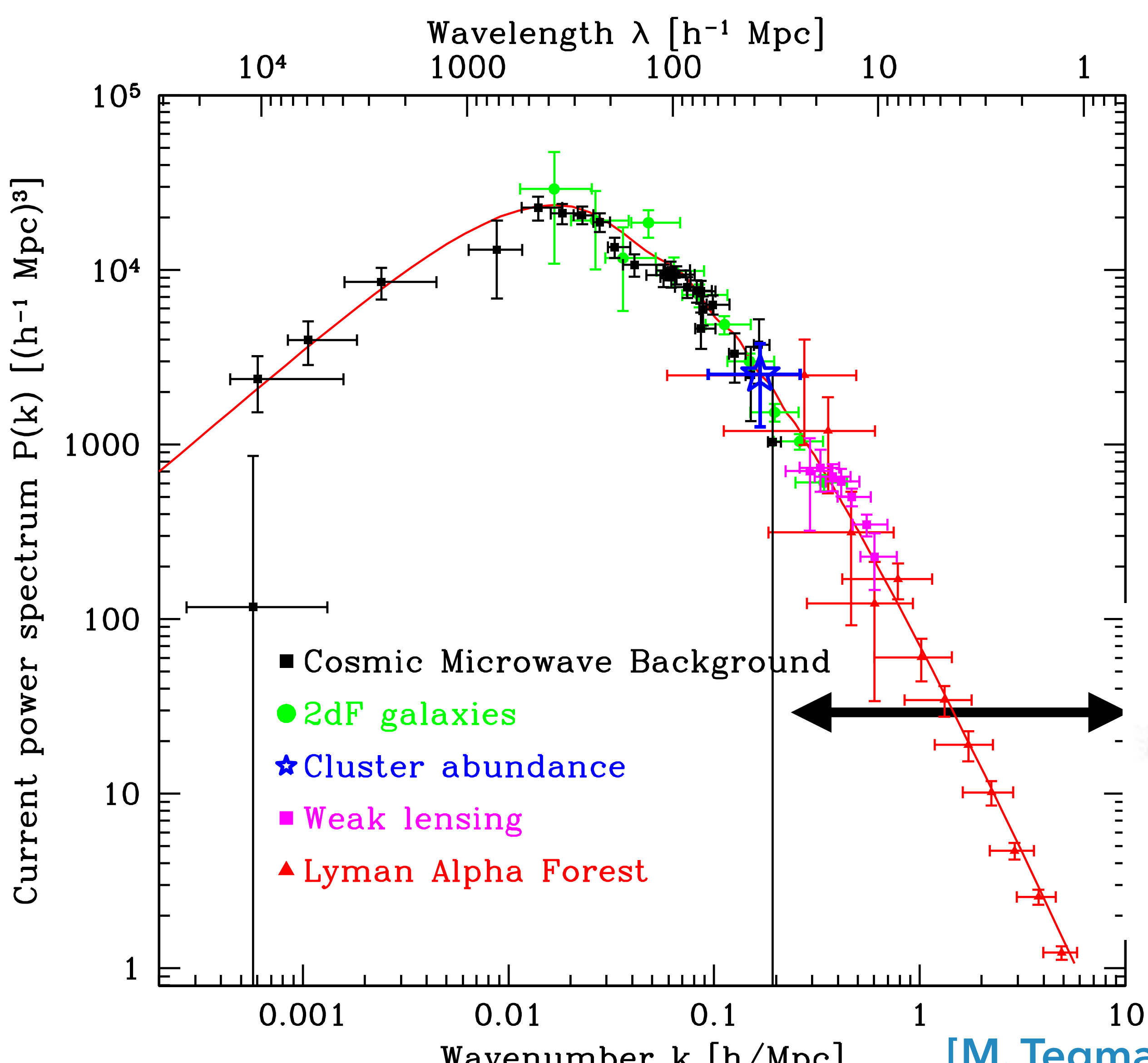
- Even if it is a real signal, lyman-alpha constraint should be studied
- We take **7 keV axino** as a benchmark

Matter power spectrum & Ly-alpha forest

- Matter distribution is calculated by cosmological perturbation theory

$$\rho_M(\vec{x},t) = \bar{\rho}_M(t) + \delta\rho_M(\vec{x},t)$$

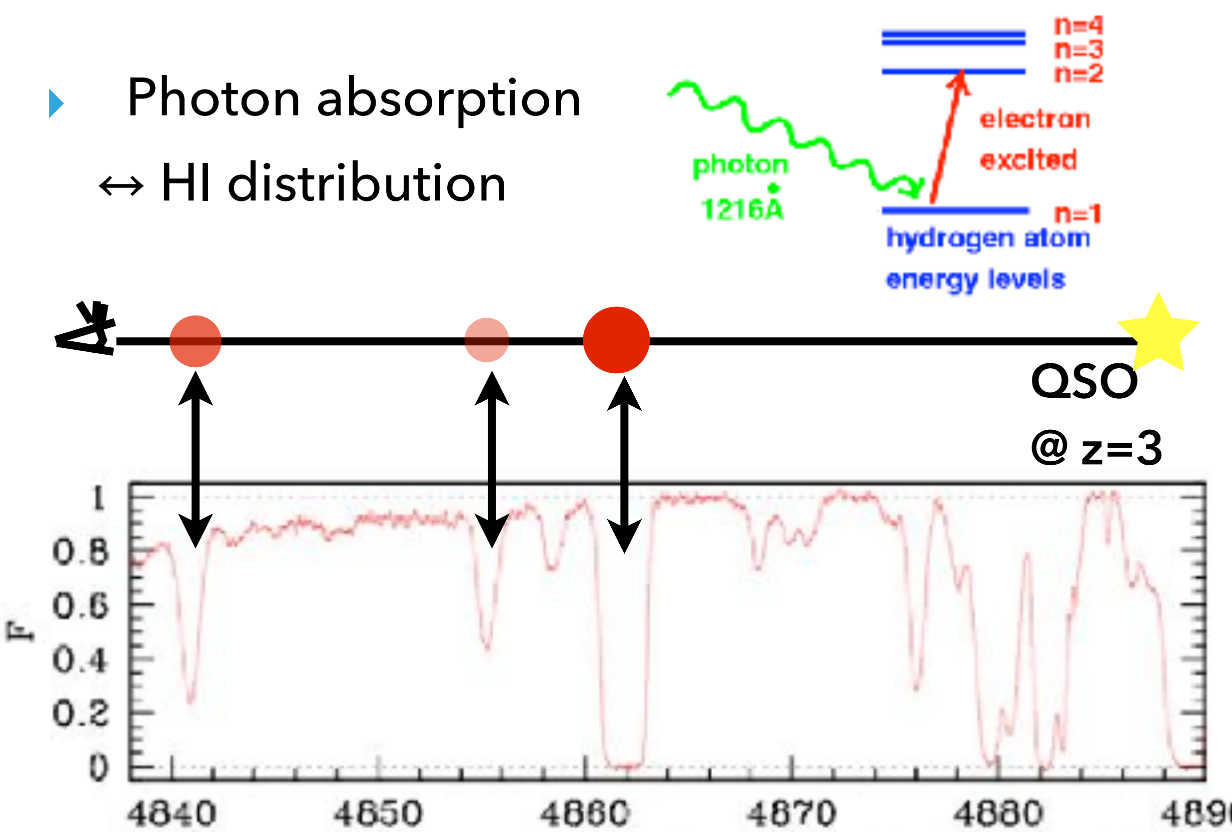
- Observable quantity is **matter power spectrum**



[M. Tegmark & M. Zaldarriaga (2002)]

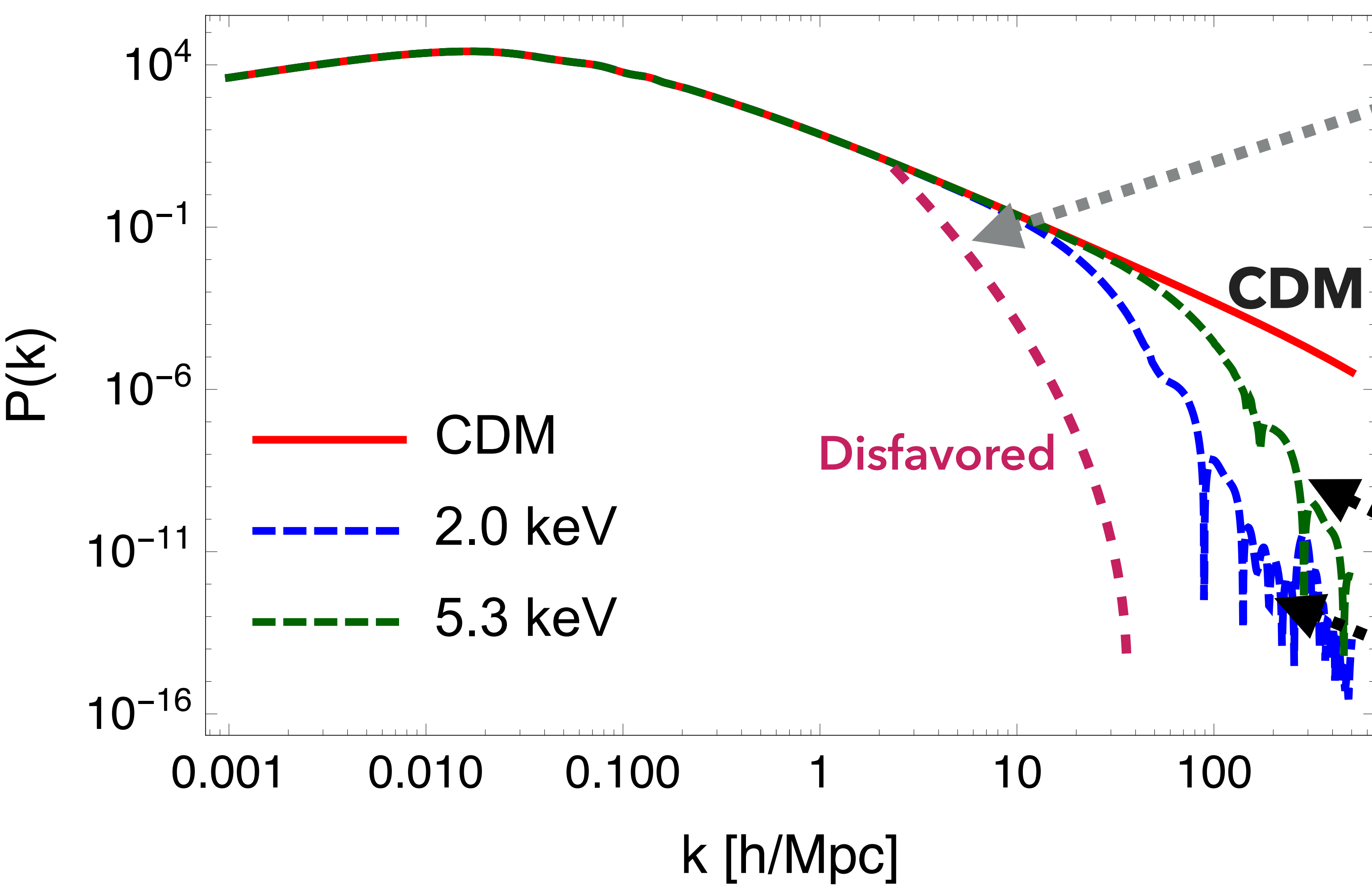
P(k) at small scale is determined by Ly-alpha forest observation

- Photon absorption
  ↔ HI distribution



Warm Dark Matter & Ly-alpha constraints

- DM free-streaming **erases the primordial density contrasts at small scale**
- Warm Dark Matter (WDM): free-streaming length is kpc - Mpc



[Numerical calculation by CLASS]

If cut-off scale k is too small, lyman-alpha forest observation disfavors the WDM model

Lyman-alpha forest constraints:

$m_{\mathrm{WDM}} > 5.3\ \mathrm{keV}$ [V. Iri et. al., (2017)]

$m_{\mathrm{WDM}} > 2.0\ \mathrm{keV}$ [M. Viel et. al., (2005)]

7 keV DM is allowed??

Meaning of "m_{WDM} > *** keV"

- Mass bound such as "m_{WDM} > 5.3 keV" assumes ***conventional WDM***
  i.e., **Fermi-Dirac distribution** w/ spin d.o.f =2

$$n_{\rm WDM} = 2\int \frac{d^3p}{(2\pi)^3}\frac{1}{e^{p/T}+1}$$

- DM abundance is determined by 2 parameters: (m_{WDM}, T_{WDM})

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

- For given m_{WDM}, T_{WDM} is determined to give observed DM abundance.
  Then one compares the theoretical prediction P(k) with the lyman-alpha forest data

→

$m_{\rm WDM} > 2.0$ keV	[M. Viel et. al., (2005)]
$m_{\rm WDM} > 3.3$ keV	[M. Viel et. al., (2013)]
$m_{\rm WDM} > 4.09$ keV	[J. Baur et. al., (2016)]
$m_{\rm WDM} > 5.3$ keV	[V. Iri et. al., (2017)]

How can we apply the Ly-alpha constraints to our model?

- Two differences from conventional WDM when considering 7 keV axino

	conventional WDM (Ly-alpha constraints)	7 keV axino (Freeze-in)
$f_{\rm DM}(p,t)$	Fermi-Dirac	Non-thermal (never thermalized)
g_*	~7000	106.75 (SM d.o.f)

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

$$T_{\rm DM} = \left(\frac{g_*(T)}{g_*(T_{\rm dec})}\right)^{1/3} T$$

- P(k) is calculated by $m_{\rm DM}$, $f_{\rm DM}(p,t)$, and $T_{\rm DM}$
- In realistic 7 keV DM models, we cannot simply compare 7 keV to $m_{\rm WDM}$ > 5.3 keV
- Axino $T_{\rm DM}$ is higher than conventional WDM, the constraint will be more severe

We need to compare matter power spectrum!

Contents

- 7 keV axino DM in SUSY DFSZ model with R-parity violation
- Phase space distribution from Boltzmann equation
- Linear matter power spectrum and Lyman-alpha constraints
- Entropy production from saxion decay

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Axino in SUSY DFSZ model

- SUSY + PQ
  - Motivated by EW naturalness and strong CP problems
  - Superpotential

PQ= -1, +1, +1

$$W_{\mathrm{DFSZ}} = \frac{y_0}{M_*} X^2 H_u H_d$$ + (PQ SSB sector)

  - After SSB of PQ symmetry, *X* generates axion *superfield*

$$X = \frac{v_{\mathrm{PQ}}}{\sqrt{2}} e^{A/v_{\mathrm{PQ}}} \qquad A = \frac{s + ia}{\sqrt{2}} + \sqrt{2}\theta\tilde{a} + \theta^2 F_A$$

saxion **axion** **axino (7 keV)**

  - 7 keV LSP axino is possible in some models

[e.g., Goto & Yamaguchi (1992); E. J. Chun & A. Lukas (1995)]

- Couplings are generated:
  - $v_{\mathrm{PQ}} \gtrsim 10^9\ \mathrm{GeV} \qquad M_* \sim 10^{16}\ \mathrm{GeV}$
  - μ term: $\mu \sim \frac{y_0 v_{\mathrm{PQ}}^2}{2M_*}$
  - Axino-Higgs-Higgsino interaction: $\frac{2\mu}{v_{\mathrm{PQ}}} \sim 10^{-8}$

Feebly Interacting Massive Particle (FIMP)

R-parity violating decay of axino

- Bilinear R-parity violation is introduced

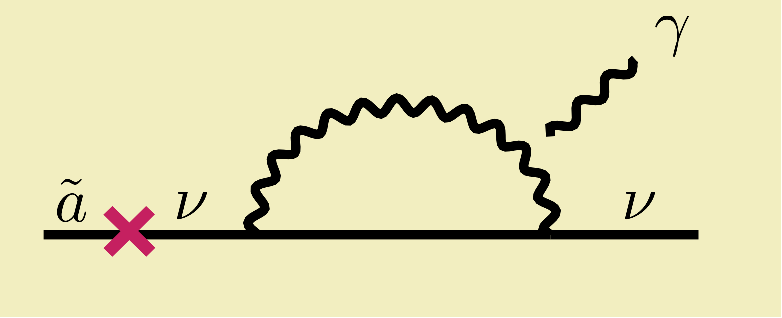
PQ= -1, +2, +1

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

- After EWSB, bRPV 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 decays as a sterile neutrino



$\sin^2 2\theta \sim 10^{-10}$ explains 3.5 keV excess!

- Other options
  - bRPV in KSVZ model ➡ Light Bino (~10 GeV) or small v_{PQ} (~10^8 GeV) required
  - sfermion 1-loop in trilinear RPV ➡ Light stau (~100 GeV) required

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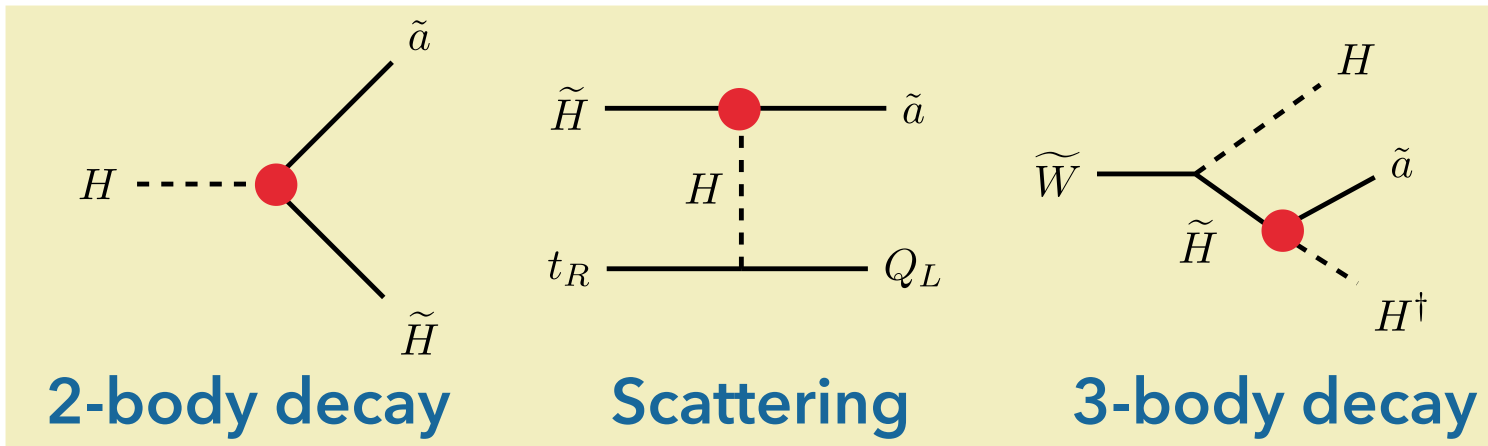
Freeze-in production of axino

- Axino is *gradually* produced by the decay or scatterings of MSSM particles
- Inverse processes are negligible due to small $n_{\tilde{a}}$

Processes



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

● **Feeble coupling ~ 10^{-8}**

- For instance, Boltzmann equation for scattering

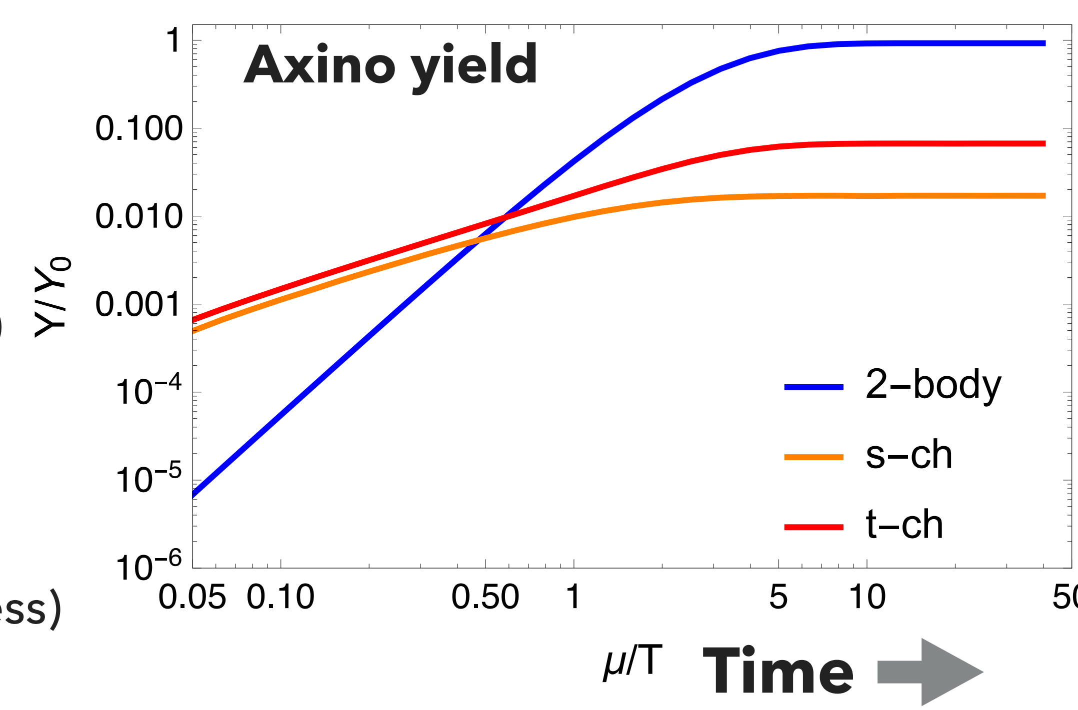
$$\dot{n}_{\tilde{a}} + 3Hn_{\tilde{a}} = \langle \sigma v \rangle \, n_1 n_2 \sim T^4 \qquad \langle \sigma v \rangle \sim 1/T^2$$

- Production is **dominated at IR** (mass of other particle)

$$Y_0 = \frac{n_0}{s_0} = \int_0^{t_0} dt \frac{\langle \sigma v \rangle \, n_1 n_2}{s} \propto \int_m^{T_R} dT M_{pl} \frac{T^4}{T^6} \sim \frac{M_{Pl}}{m}$$

(m=μ for Higgsino process)

NLSP contribution is dominant



Boltzmann Equation for phase space distribution

- For matter power spectrum, we need axino **phase space distribution** $f_{\tilde{a}}(t,p)$
- Axino is never thermalized due to its feeble interaction with MSSM particles
- After production, axino phase space distribution is just **redshifted**

Boltzmann Eq.

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

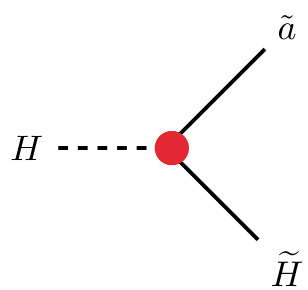
Collision term neglect axino density $f_{\tilde{a}} \simeq 0$

$$\frac{g_{\tilde{a}}}{E_{\tilde{a}}} C_{1+2+\cdots\to\tilde{a}+3+4+\cdots}(t,p_{\tilde{a}}) = \frac{1}{2E_{\tilde{a}}} \int \prod_{I\neq\tilde{a}} \frac{d^3p_I}{(2\pi)^3 2E_I} (2\pi)^4 \delta^4(\hat{p}_1 + \hat{p}_2 + \cdots - \hat{p}_{\tilde{a}} - \hat{p}_3 - \hat{p}_4 - \cdots)$$
$$\times \sum_{\text{spin}} |\mathcal{M}_{1+2+\cdots\to\tilde{a}+3+4+\cdots}|^2 f_1 f_2 \cdots (1\mp f_3)(1\mp f_4)\cdots$$

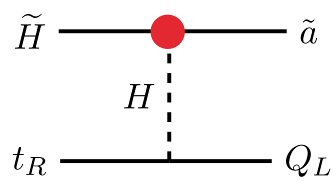
- Integrating Boltzmann Eq., we obtain phase space distribution

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

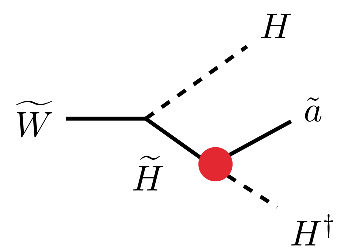
Axino momentum distribution: channel dependence



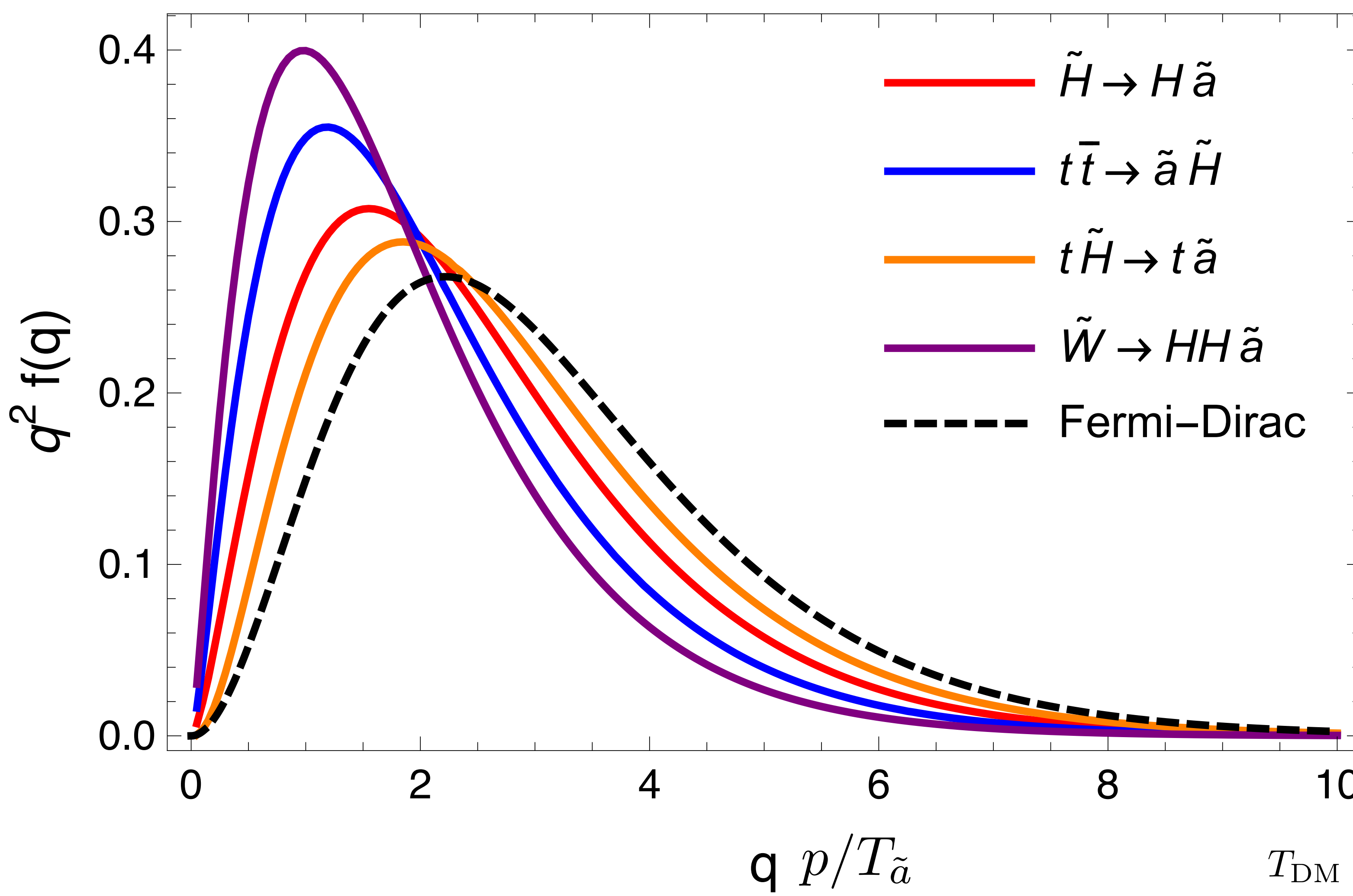
2-body decay



Scattering



3-body decay



$$T_{\rm DM} = \left(\frac{g_*(T)}{g_*(T_{\rm dec})}\right)^{1/3} T$$

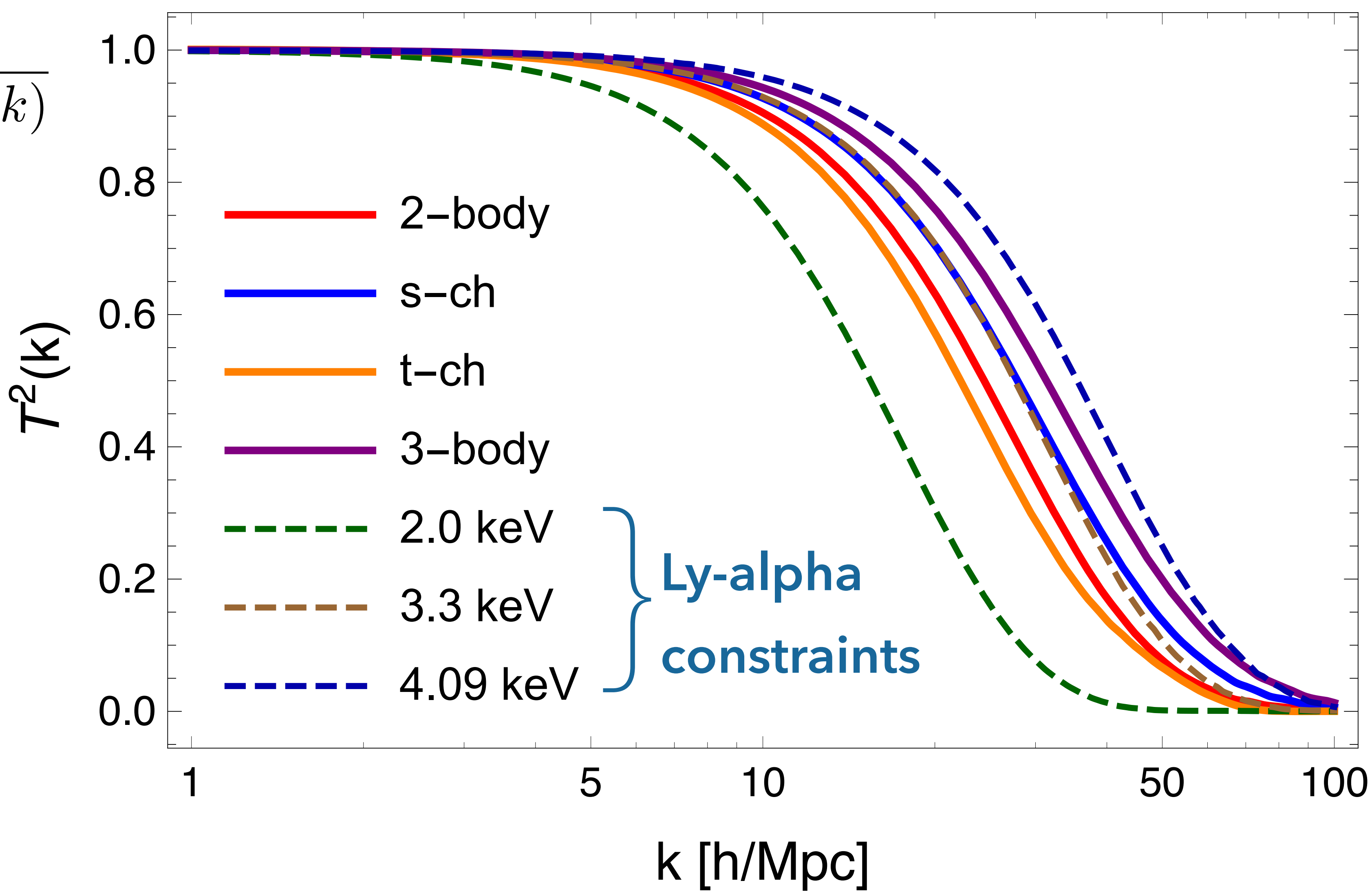
- Distribution is different for different production process
- **Colder** than Fermi-Dirac distribution

Matter power spectrum: channel dependence

- We solve cosmological perturbation equations taking axino distributions as inputs

[Numerical calculation by CLASS]

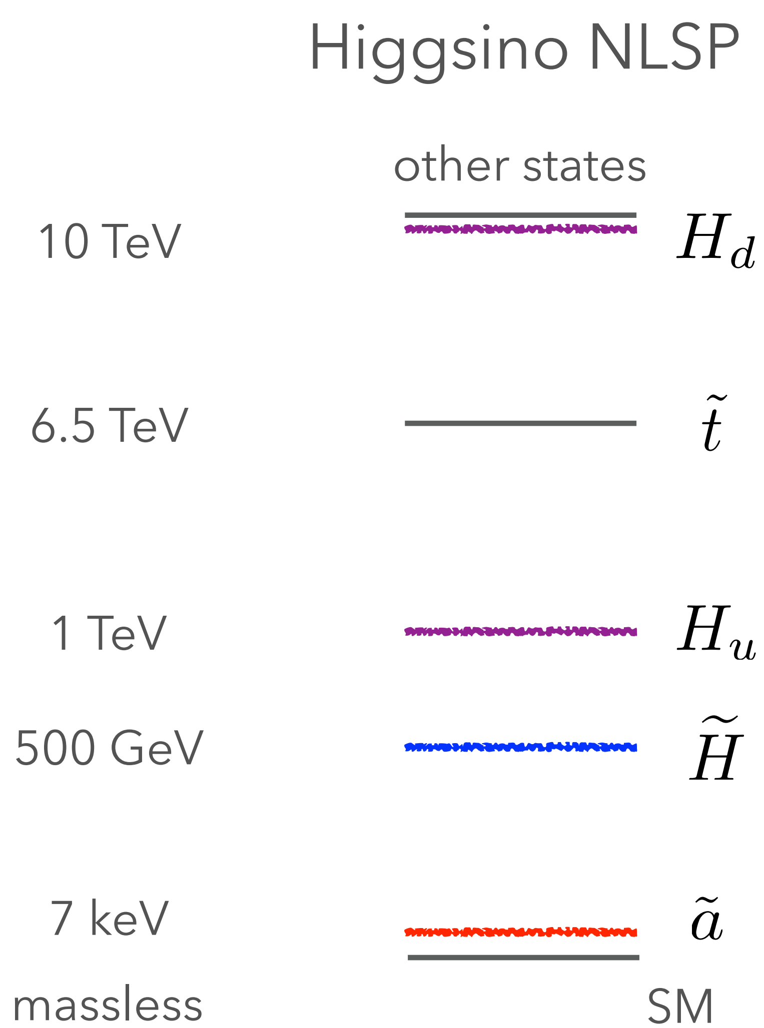
$$T^2(k) = \frac{P(k)}{P_{\rm CDM}(k)}$$

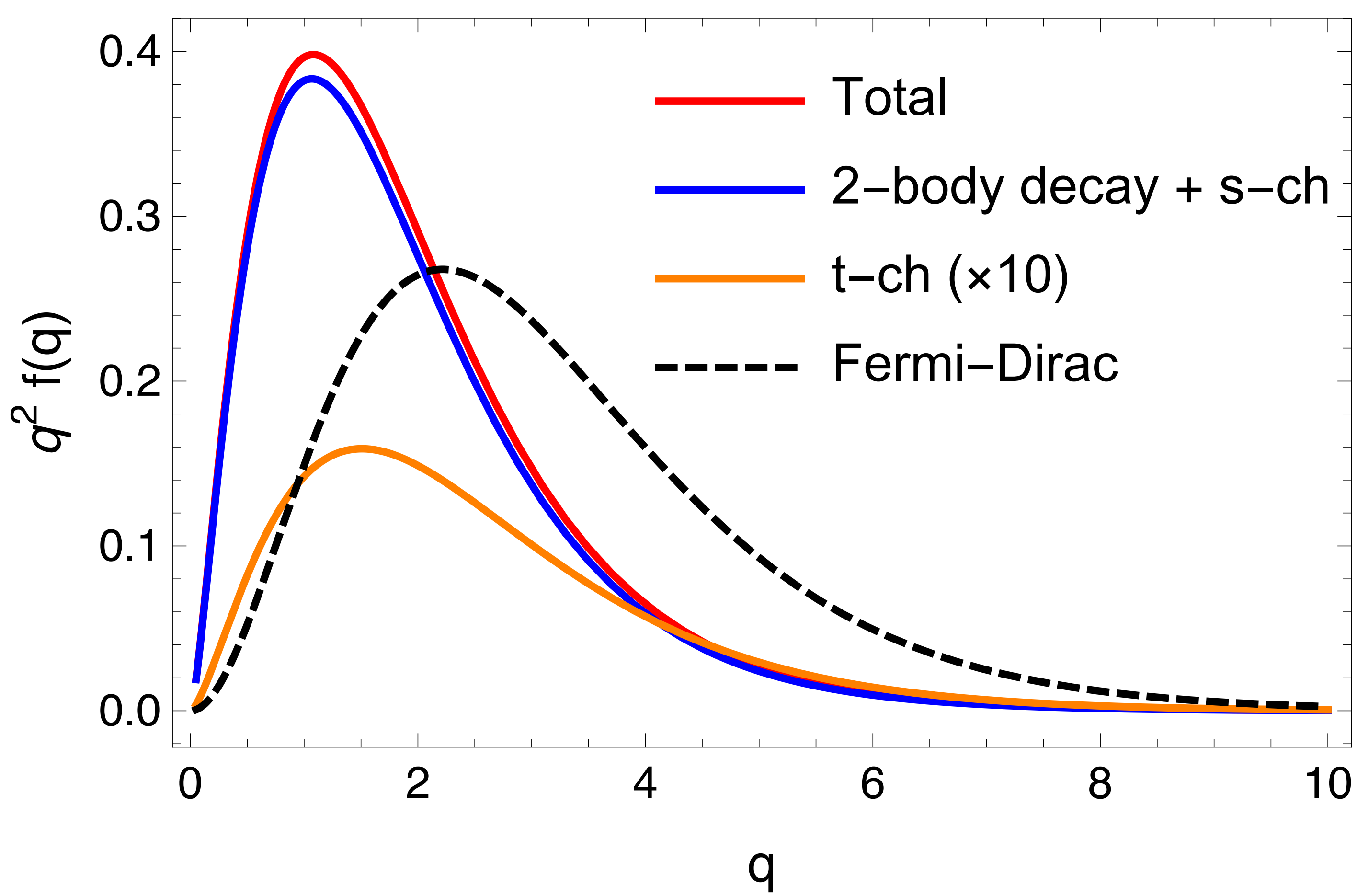


- We may expect that $m_{\rm WDM}$ > 4.09 keV excludes 7 keV axino DM ***even for the coldest distribution from 3-body decay***

Axino momentum distribution: a realistic model

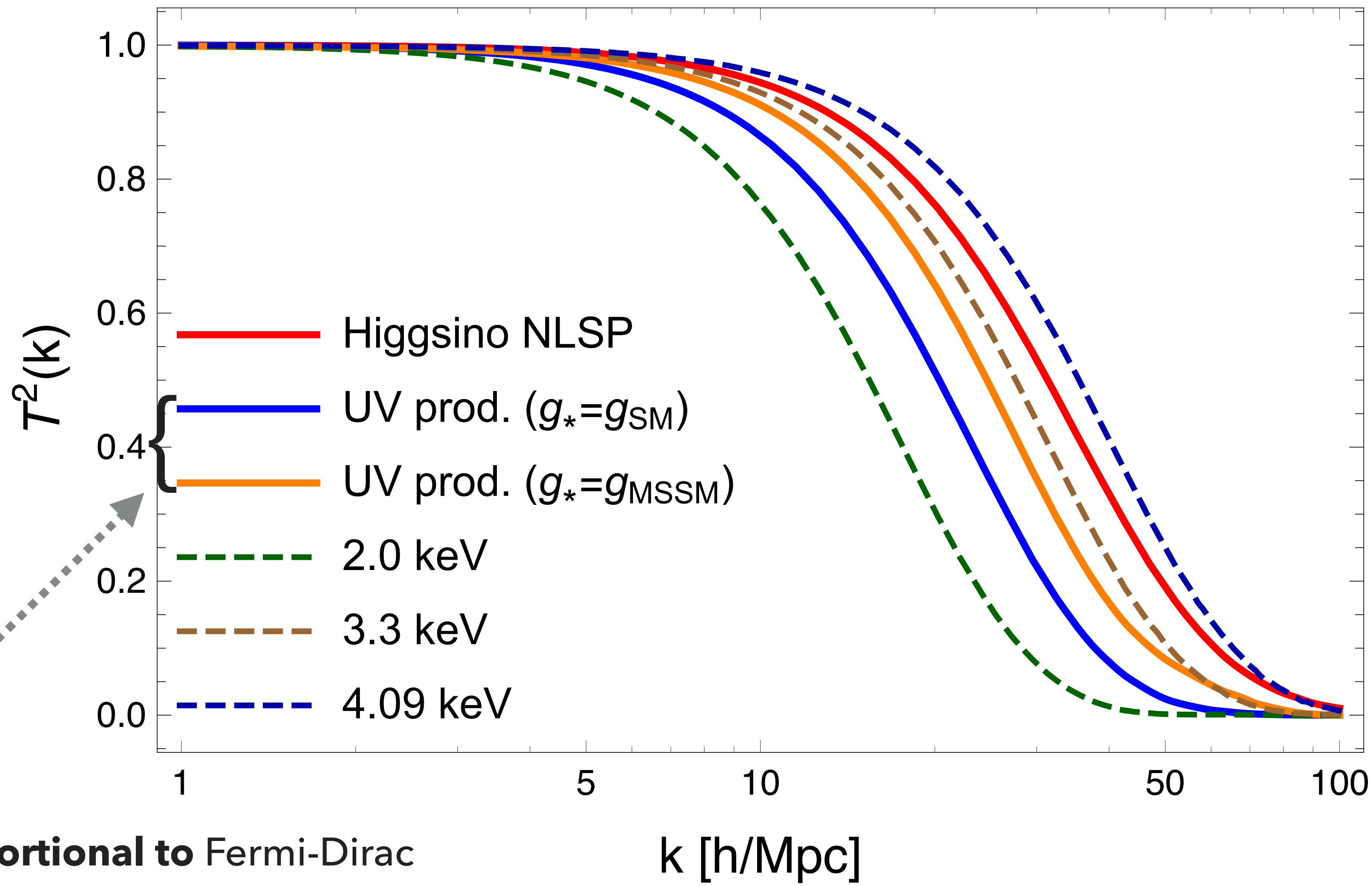
- Axino distribution in a realistic model is ***superposition*** of several processes
- We study a benchmark point to confirm the tension with lyman-alpha forest





Dominant production channel is $H \rightarrow \widetilde{H} + \tilde{a}$

Matter power spectrum: a realistic model



distribution **proportional to** Fermi-Dirac (for comparison)

- As expected, m_{WDM} > 4.09 keV disfavors the benchmark point
- 7 keV axino DM has tension with the lyman-alpha observation

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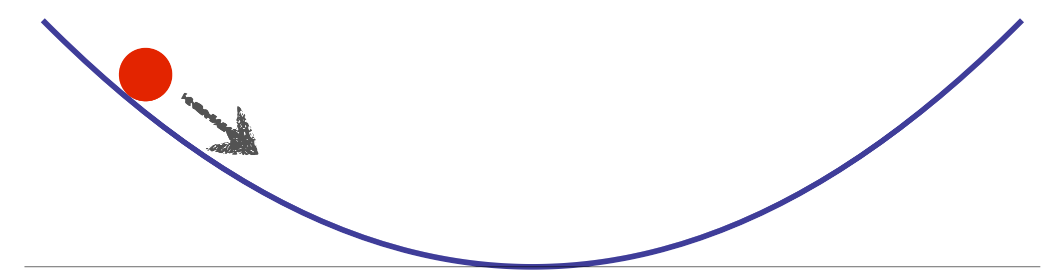
How to evade Ly-alpha constraint?

- Entropy production

- Saxion is produced by coherent oscillation

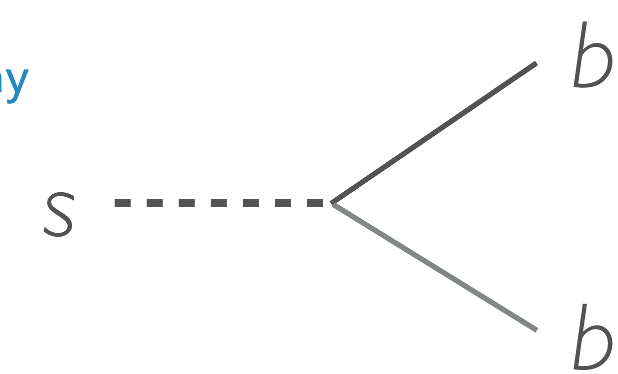


$$Y_s^{\rm CO} \simeq 1.9 \times 10^{-6} \left(\frac{\rm GeV}{m_s}\right)\left(\frac{\min[T_R, T_s]}{10^7\,{\rm GeV}}\right)\left(\frac{s_0}{10^{12}\,{\rm GeV}}\right)^2$$

- At some later time, saxion dominates the universe

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

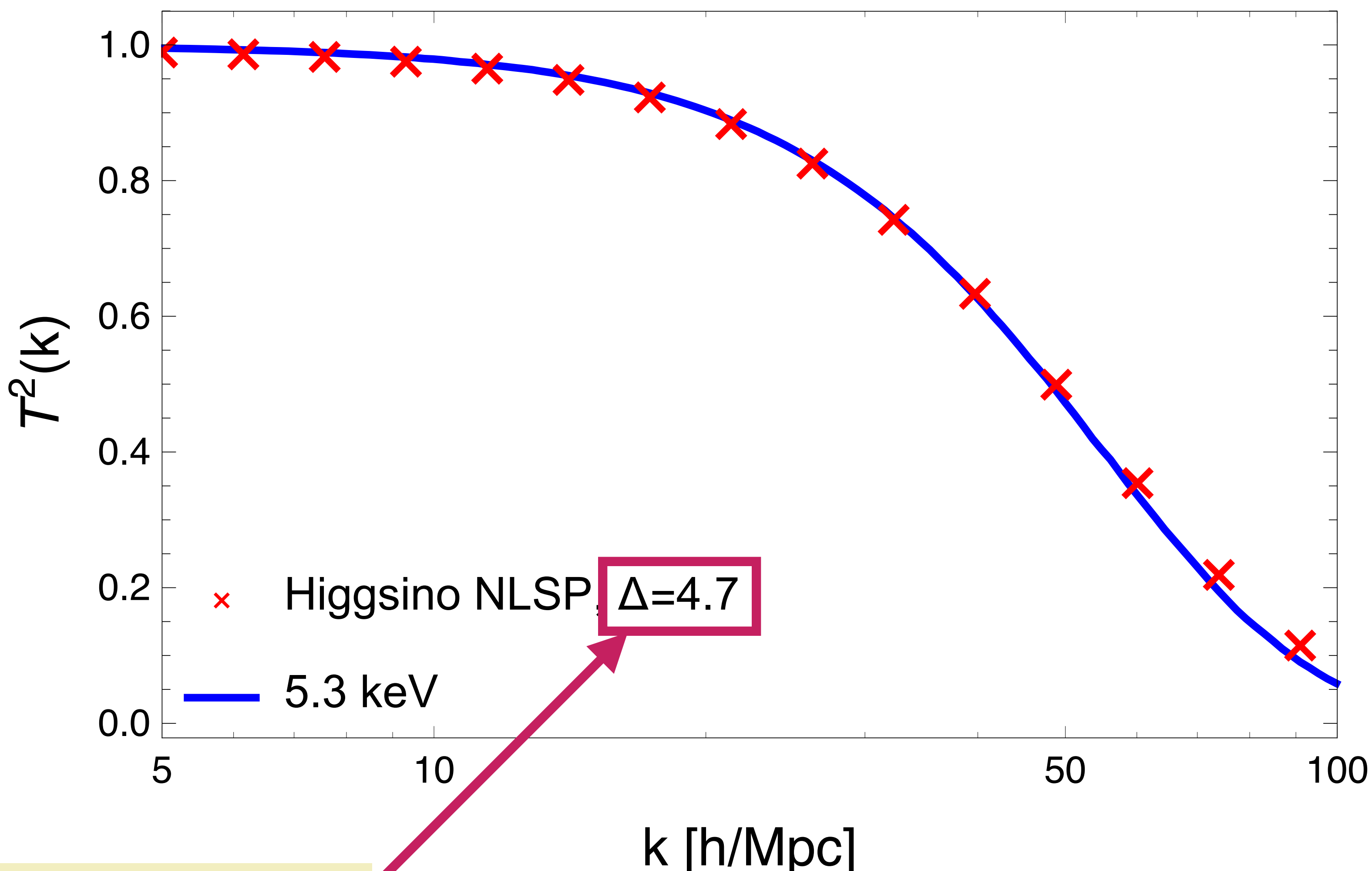
- Then saxion decays **after axino production** and heats up only SM plasma
  - Entropy prouction $\Delta = \frac{s_f}{s_i} \simeq \frac{T_e^s}{T_D^s}$ Temperature after saxion decay
  - Axino temperature decreases $T_{\tilde a} \to T_{\tilde a}\Delta^{-1/3}$



How to evade Ly-alpha constraint?

- Entropy production

- With Δ=4.7, the strongest Ly-alpha constraint m_{WDM} > 5.3 keV is evaded!



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

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

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

DM abundance is also explained!

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

Summary

- 7 keV DM (motivated by 3.5 keV excess) models should be tested by the lyman-alpha forest observation
- To do so, we need to calculate DM phase space distribution and resultant matter power spectrum
- 7 keV axino WDM (and possibly other proposed 7 keV DMs) has tensions with the recent strong lyman-alpha forest constraint $m_{WDM} > 5.3$ keV
- In SUSY axion model, inherent entropy production from saxion decay alleviates the tension

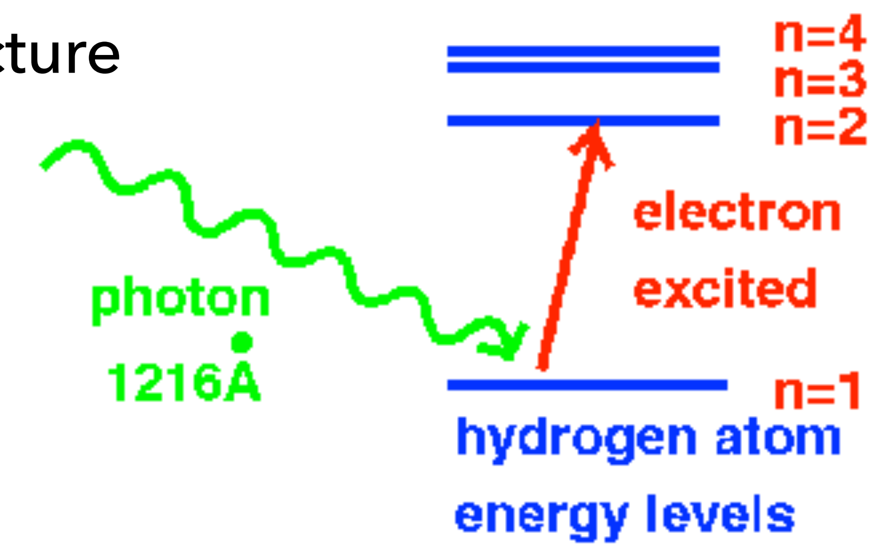
Backup

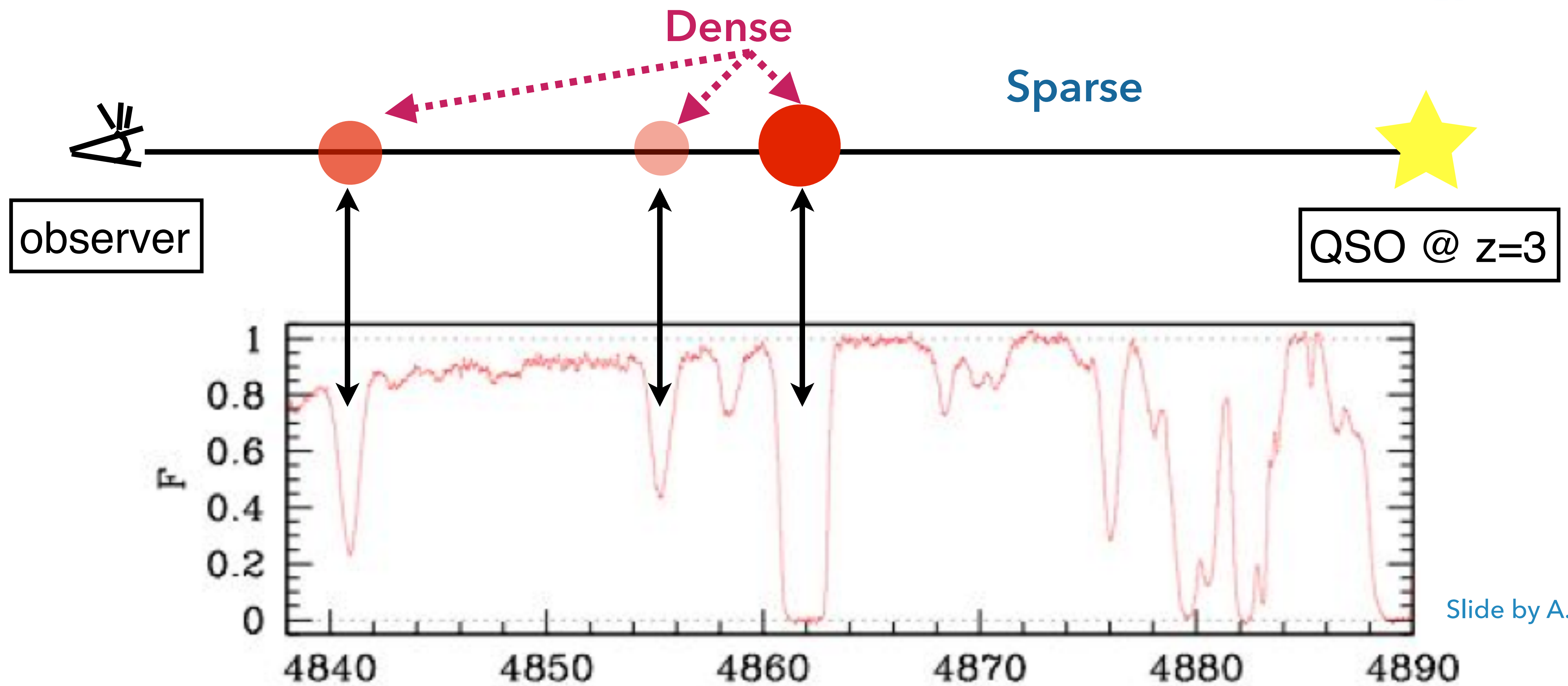
Ly-a forest observation

- Important constraints on light DM from cosmic structure
- absorption intensity/frequency

  ↔ HI distribution along the line-of-sight

  ➡ **Matter distribution** of the universe

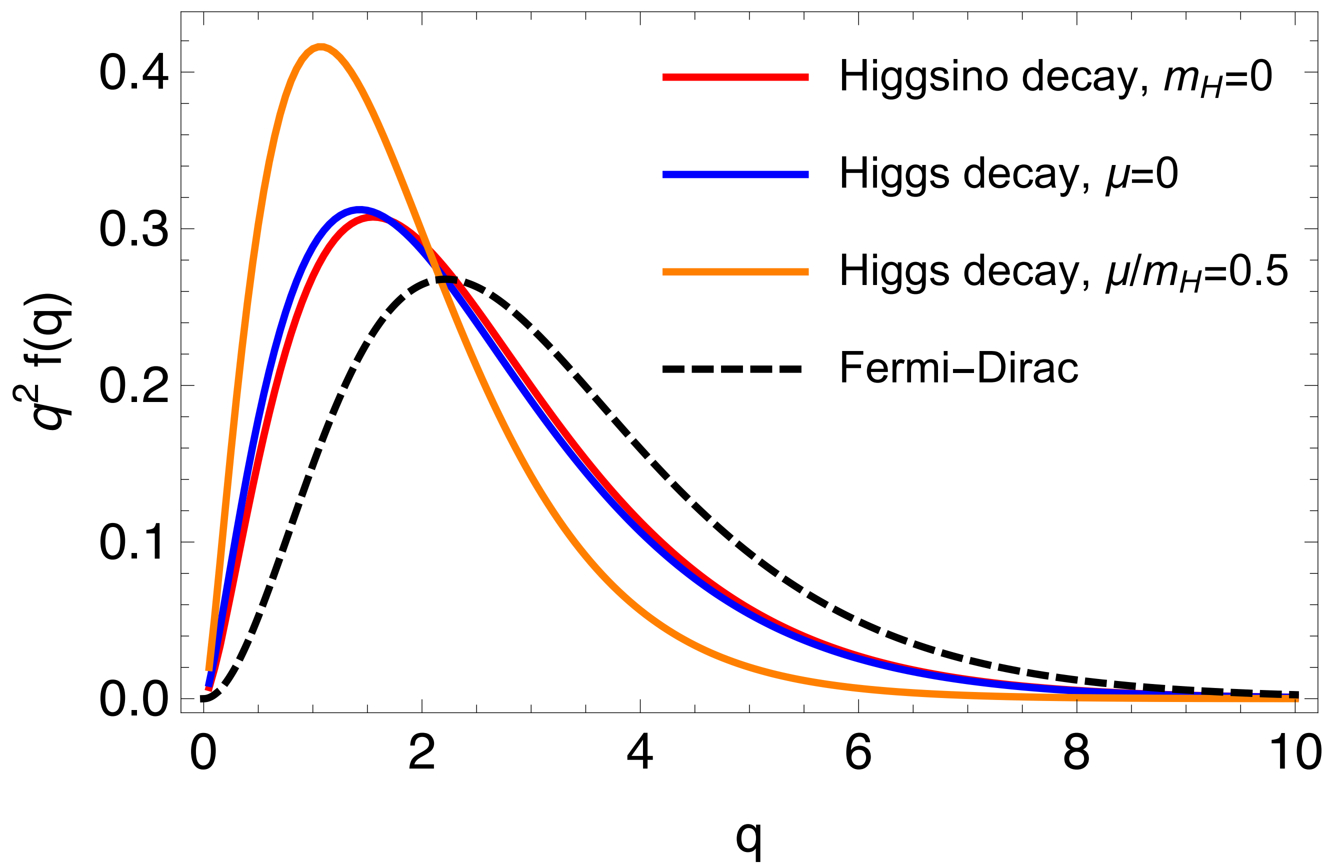




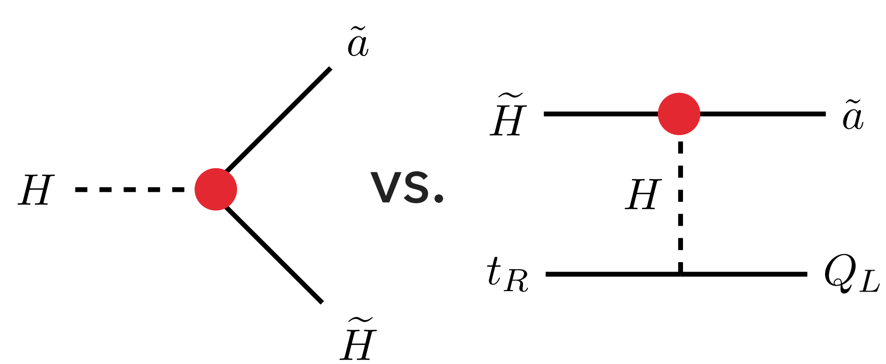
Slide by A. Kamada

How to evade Ly-alpha constraint?

- Mass degeneracy



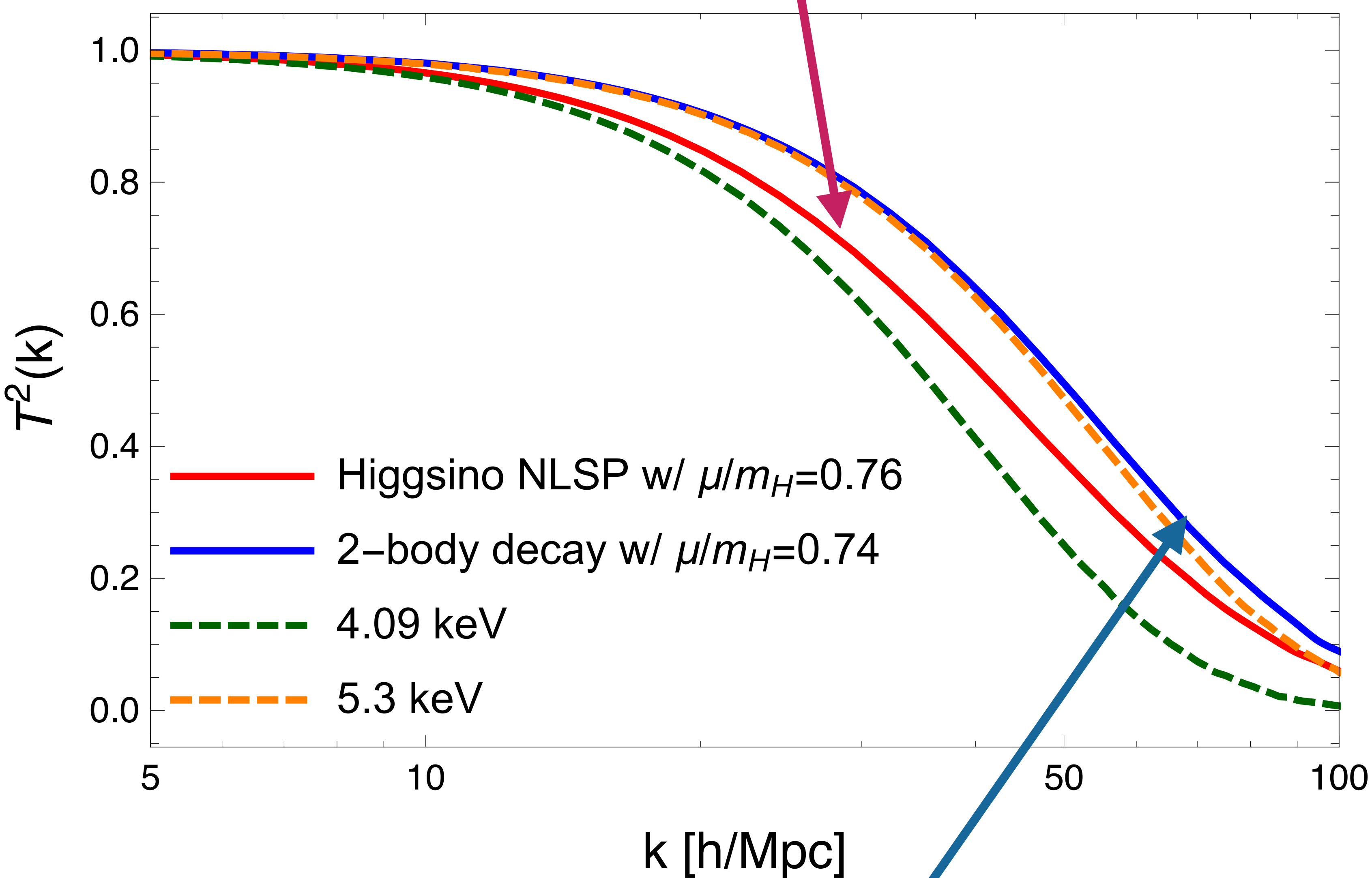
- Axino distribution is colder for compresses mass spectrum
- However, **scattering > 2-body decay** for very degenerate case



How to evade Ly-alpha constraint?

- Mass degeneracy

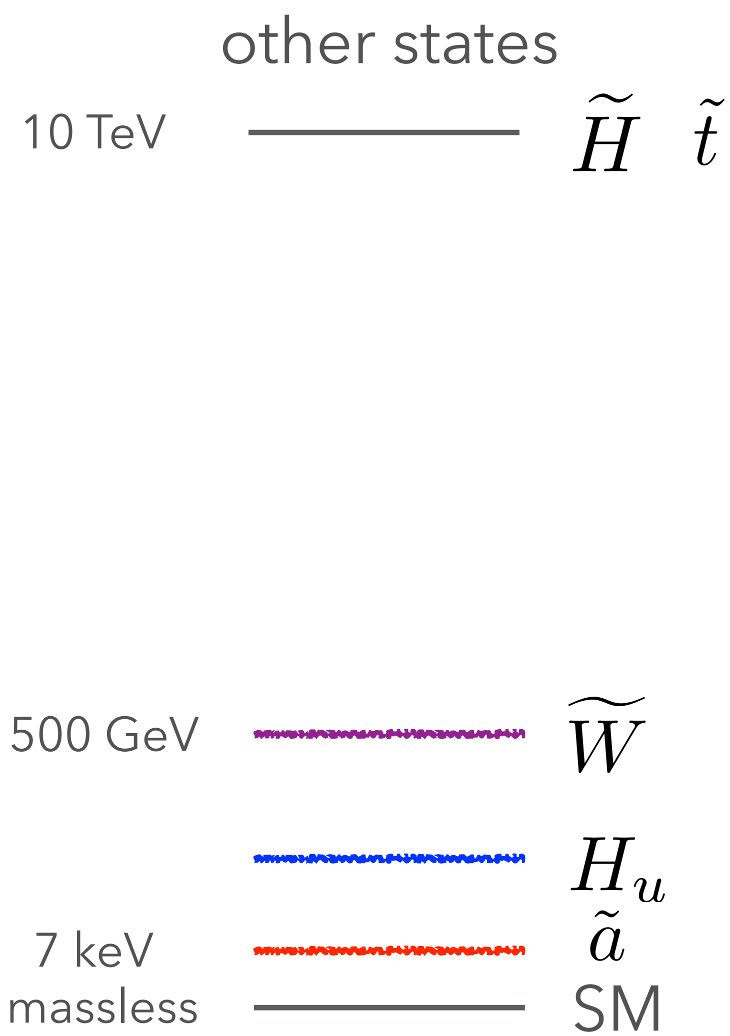
Realistic axino models w/ Higgsino NLSP cannot become colder than this line



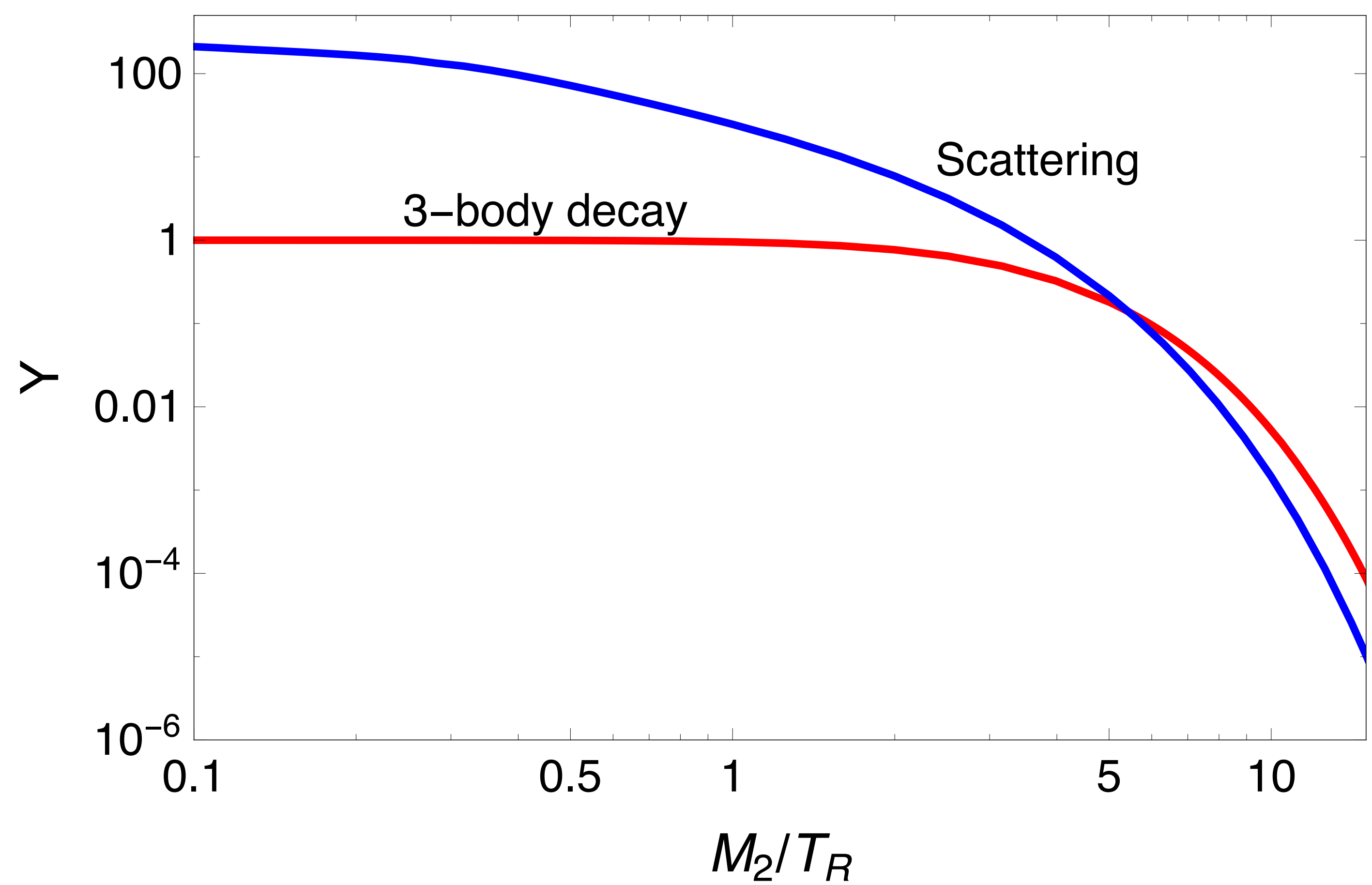
If only 2-body decay exists, m_{WDM} > 5.3 keV can be evaded

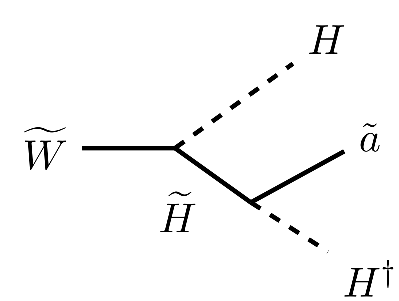
Another benchmark

Wino NLSP



3-body decay vs. scattering





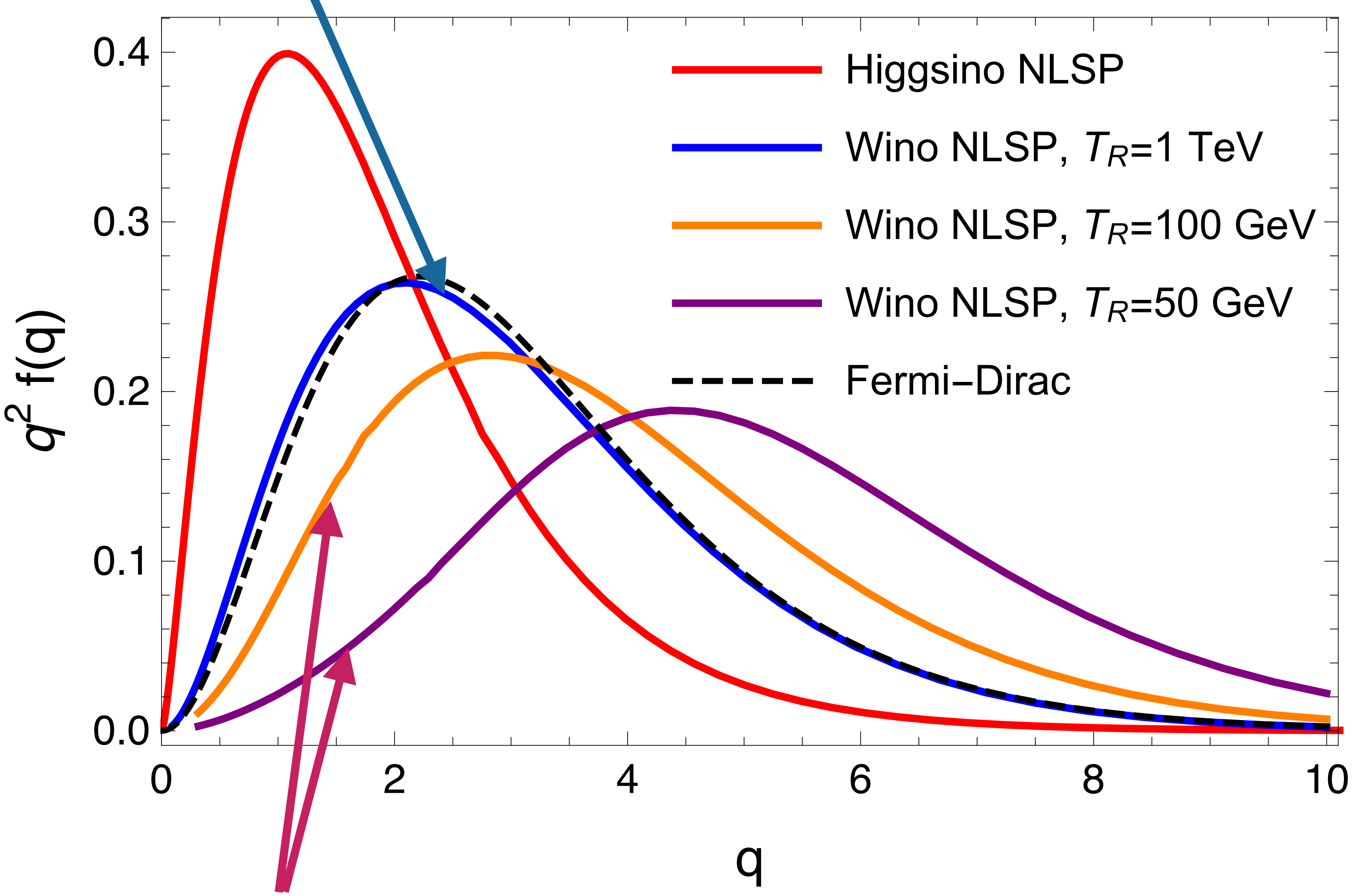
= dim. 5

→ efficient at UV

- $T_R > M_2$: 2-to-2 scattering dominates
- $T_R < M_2/5$: Wino 3-body decay dominates

Another benchmark

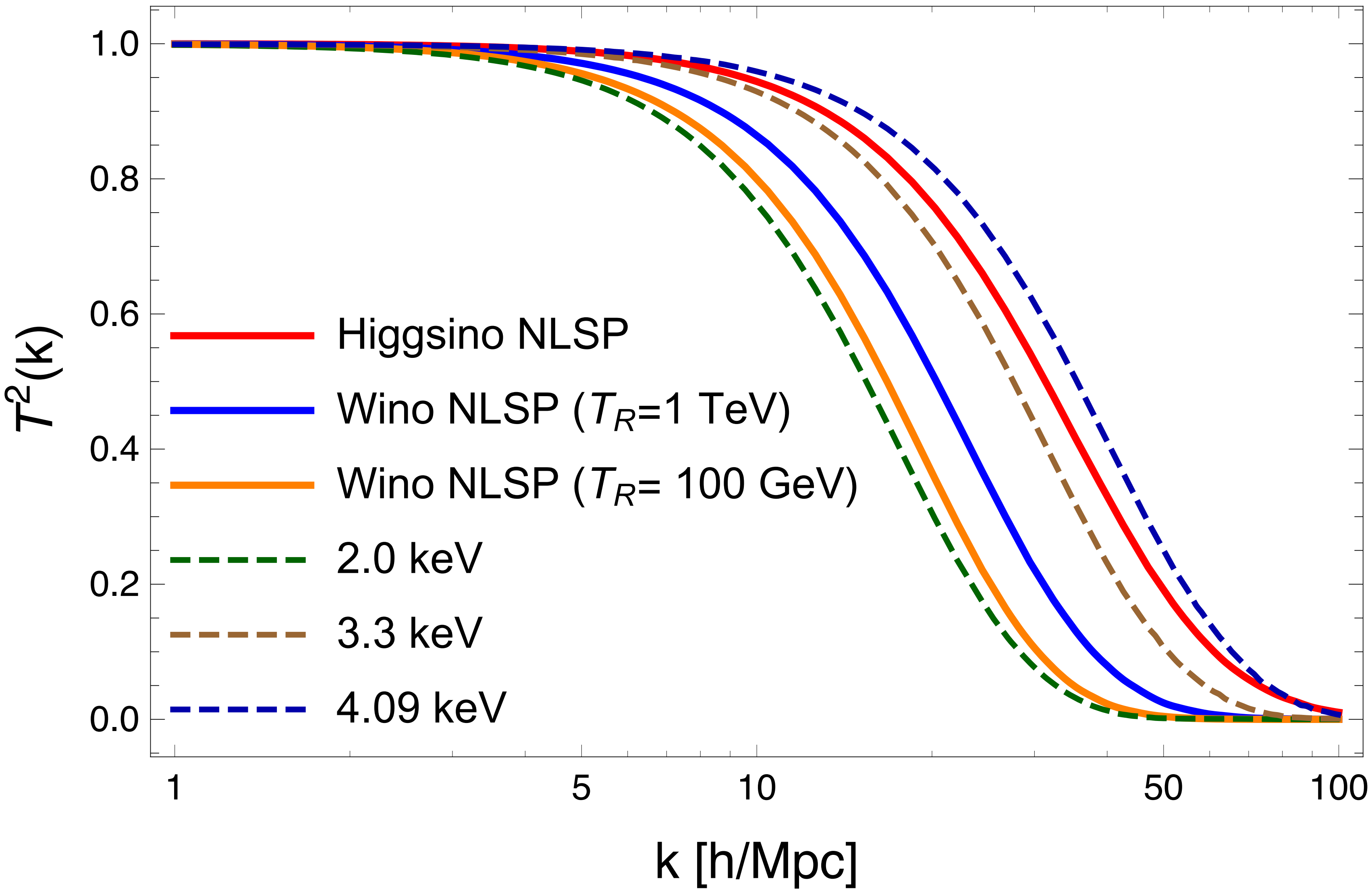
UV production produces thermal-like distribution



3-body decay dominant, but **hotter** than thermal one

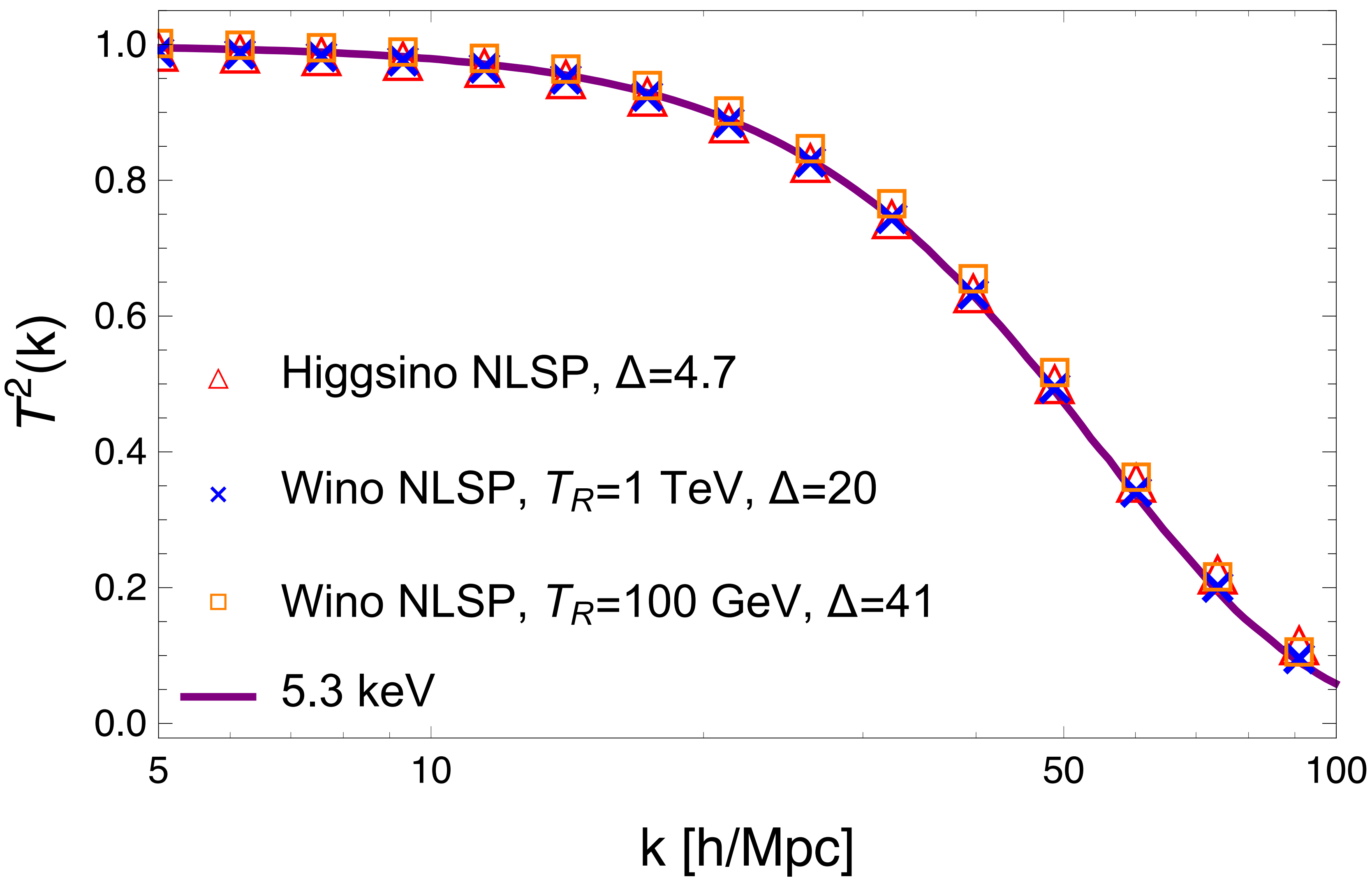
$T_R < M_2/5$ implies axino energy ($\sim M_2/3$) is larger than temperature

Another benchmark



- Wino NLSP cases are disfavored by m_{WDM} > 3.3 keV

Another benchmark



- Saxion decay alleviates the tension
- But Δ is large and difficult to realize without spoiling BBN

  $T_e^s \sim 2.5 - 25\ \mathrm{MeV}$ (saxion domination)

- 110 GeV saxion decay into SM fermion pair, and dominantly into bb
- Because it comes from mixing with Higgs, decay rate is proportional to yukawa
- Anomaly term for gluon comes from MSSM quark (squark) loop, so it is not proportional to reheating temperature unless it is below squark or gluino mass

How can we apply the Ly-alpha constraints to our model?

- Two differences from conventional WDM when considering 7 keV axino

1. Phase space distribution is not always Fermi-Dirac (thermal)

Distribution is very **model-dependent** (e.g., freeze-in DM is never thermalized)

Free-streaming length is different for different distributions

2. DM "Temperature" is determined by g_* at the DM decoupling

Typically, g_{SM} = 106.75 or g_{MSSM} =226.75 is adopted

But bounds such as m_{WDM} > 5.3 keV assume **very large g_*** (large entropy production)

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

$$\Rightarrow \quad g_{*,{\rm WDM}} \sim 7000$$

- In realistic 7 keV DM models, we cannot simply compare 7 keV to m_{WDM} > 5.3 keV

We need to compare matter power spectrum!