keV Freeze-in Axinos & Lyman-alpha forest constraint

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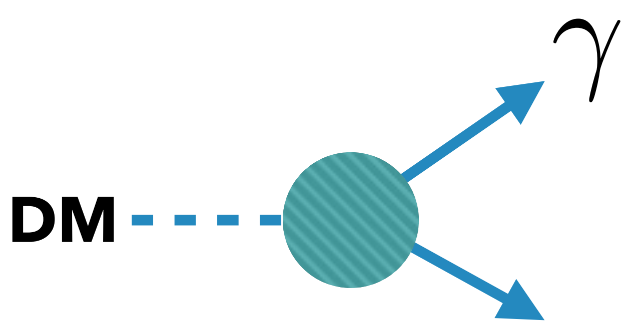
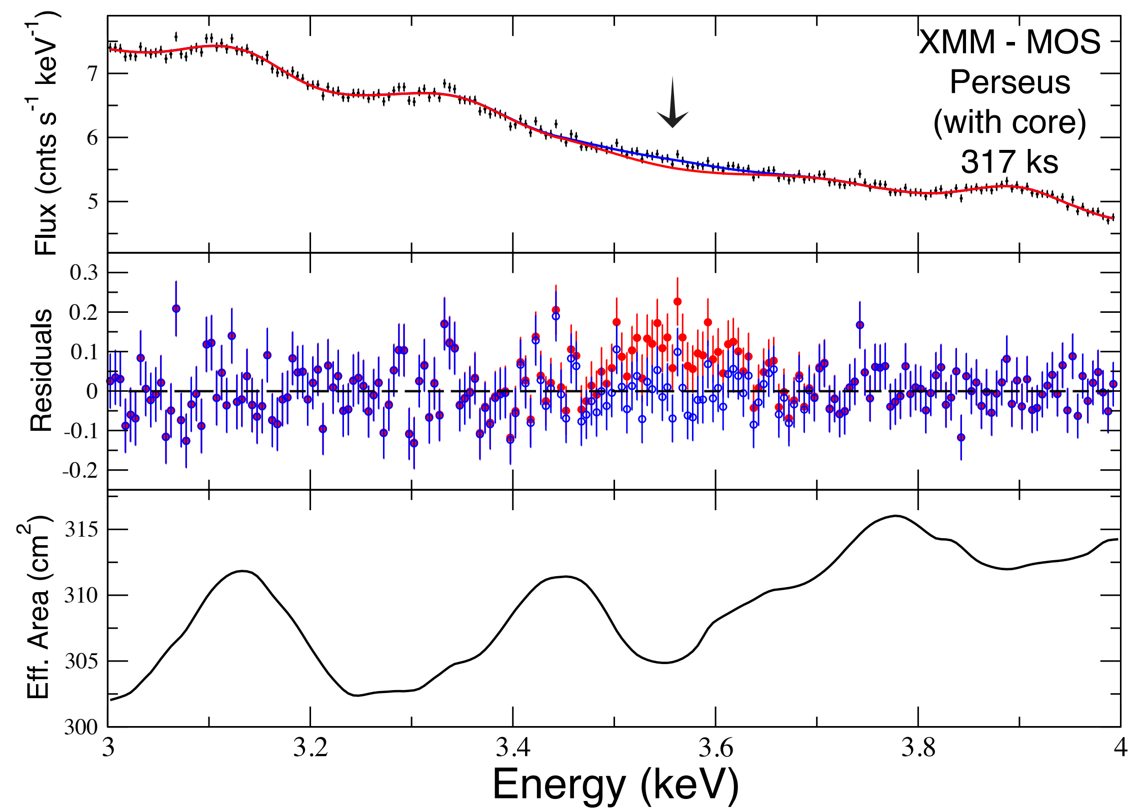
3.5 keV X-ray excess?

Rare decay of **7 keV** DM?

From Perseus galaxy cluster, Andromeda galaxy…

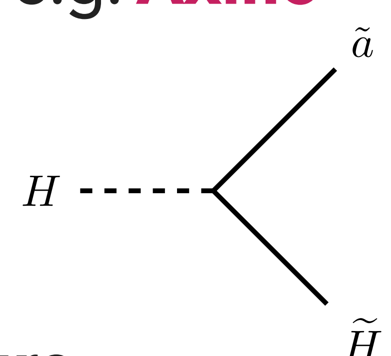


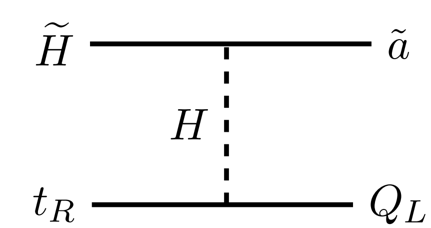


A lot of models have been proposed

- One popular production mechanism is **Freeze-in**
- Freeze-in DM is produced by **rare** interactions of particles in thermal plasma
- 7 keV DM **warmness** is constrained by **cosmic structure**

e.g. **Axino**

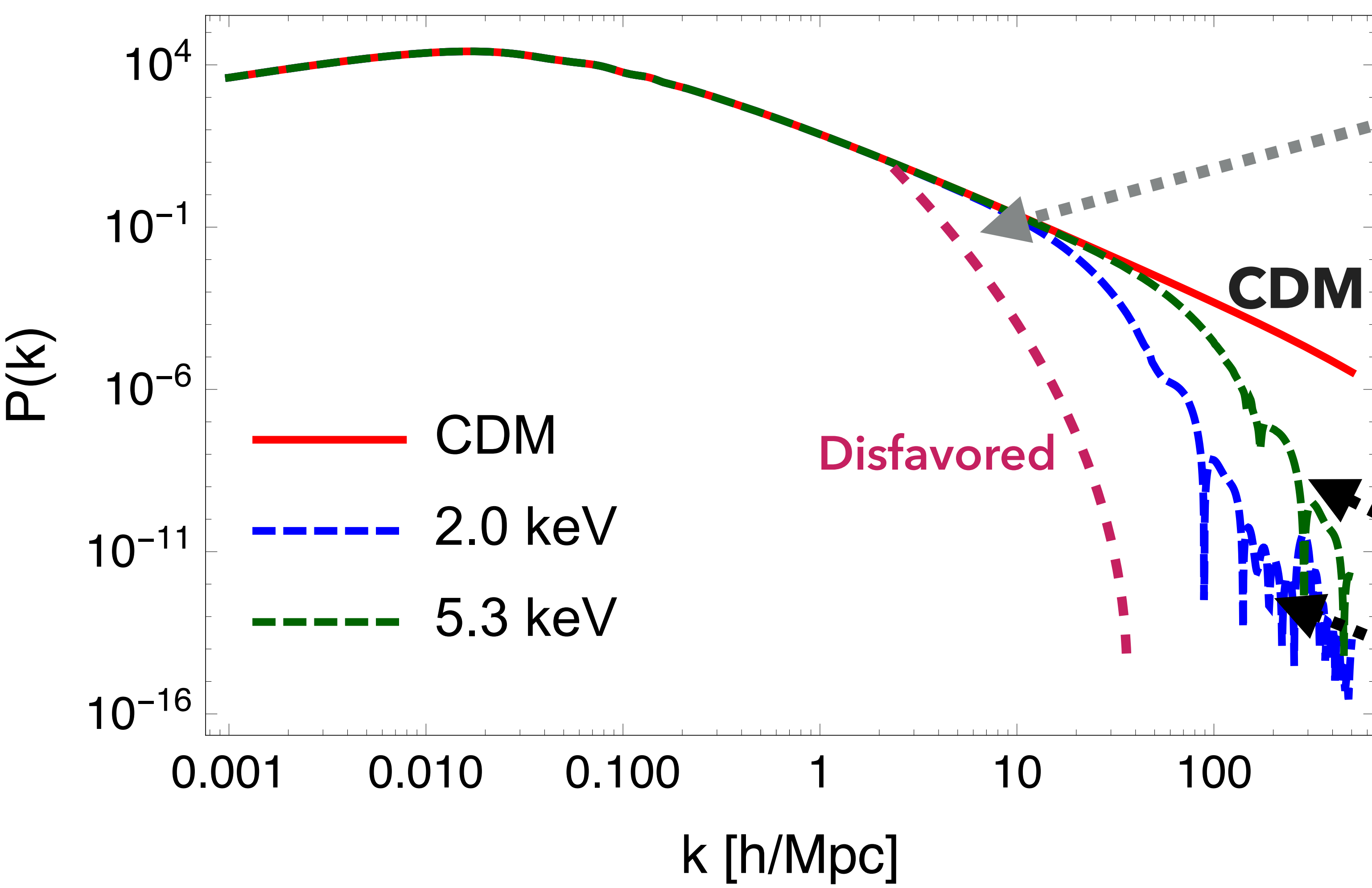




DM warmness vs. Ly-alpha forest constraints

DM free-streaming **erases the primordial density contrasts at small scale**

- WDM shows **cut-off** for matter power spectrum, which means less seed for structure
- The smallest scale is constrained by **Ly-alpha**: HI absorption ↔ matter distribution



[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??

How can we apply the Ly-alpha constraints to Freeze-in DM?

It is not straightforward to apply Lyman-alpha constraints to **Freeze-in DM**

P(k) is calculated by $m_{\rm DM}$, $f_{\rm DM}(p,t)$, and $T_{\rm DM}$

	WDM which Ly-alpha constraints	Freeze-in DM (e.g. axino)
$f_{\rm DM}(p,t)$	Fermi-Dirac	**Non-thermal**
g_*	**~7000**	Typically, 106.75 (SM d.o.f)

$$\Omega_{\rm WDM}h^2 = \left(\frac{m_{\rm WDM}}{94{\rm eV}}\right)\left(\frac{T_{\rm WDM}}{T_\nu}\right)^3 = 7.5\left(\frac{m_{\rm WDM}}{7{\rm keV}}\right)\left(\frac{106.75}{g_*^{\rm WDM}}\right) \qquad T_{\rm DM} = \left(\frac{g_*(T)}{g_*(T_{\rm dec})}\right)^{1/3} T$$

- Temperature and momentum distribution are very different
- In realistic 7 keV DM models, we cannot simply compare 7 keV to $m_{\rm WDM}$ > 5.3 keV

We need to compare matter power spectrum directly!

Freeze-in production of axino

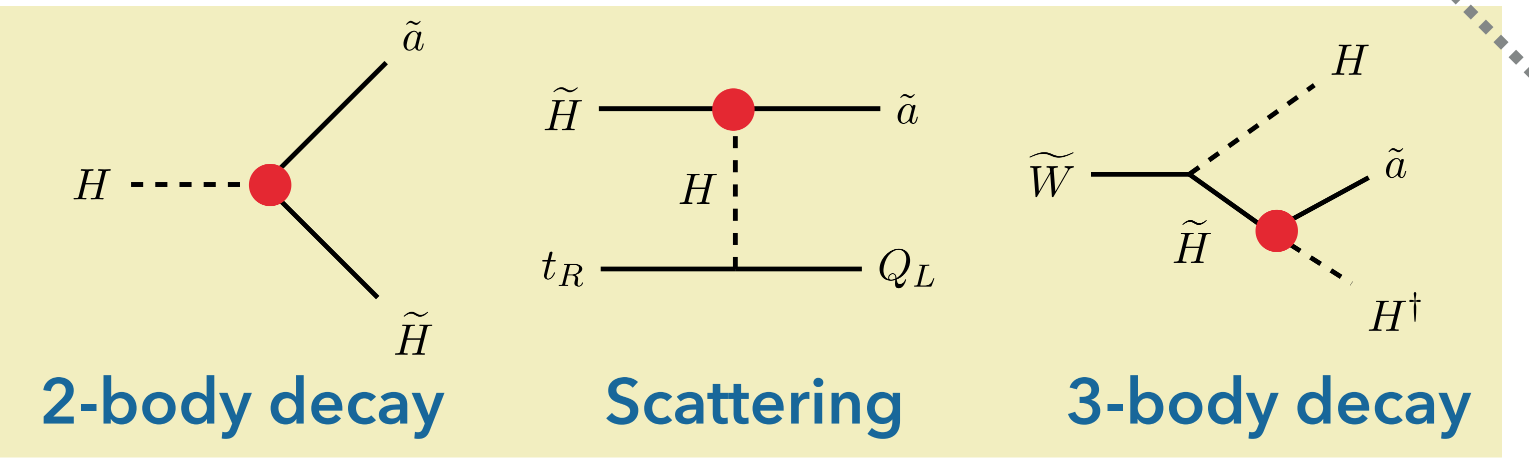
- We take 7 keV axino as a benchmark model
- Inverse processes are negligible due to small $n_{\tilde{a}}$

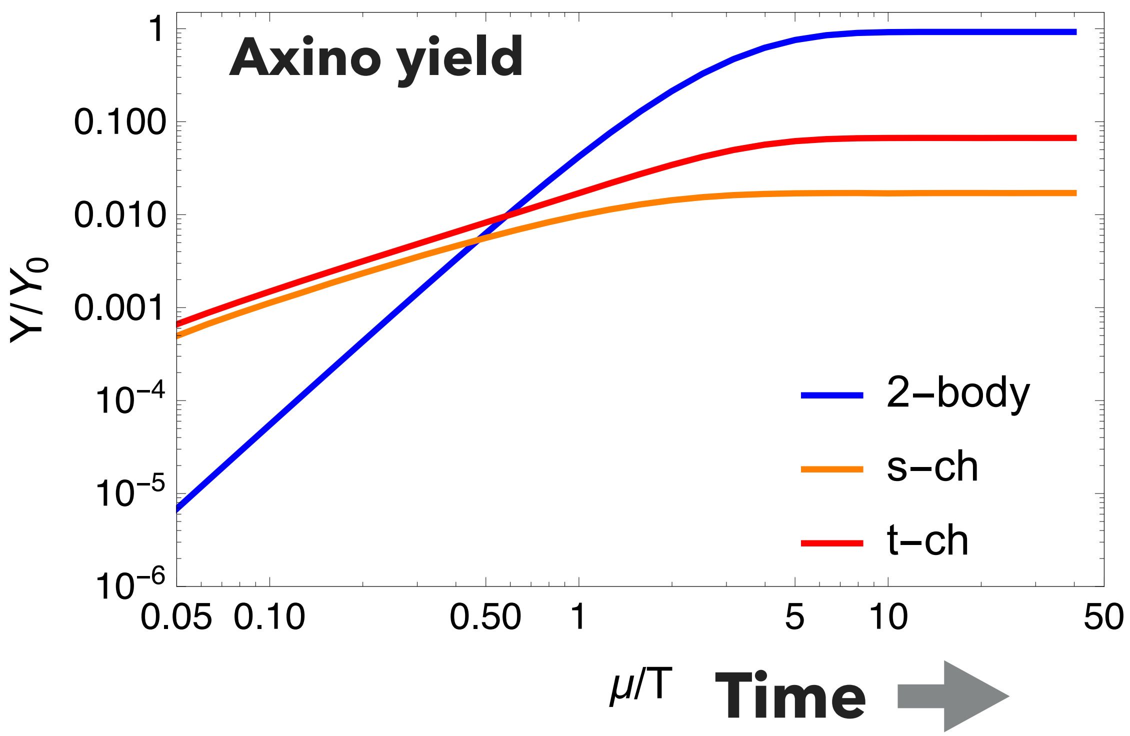
$$\mathcal{L} \sim \frac{2\mu}{v_{\rm PQ}} \tilde{a}\tilde{H}H$$

(See also K. J. Bae's talk on Friday)

Feeble coupling ~ 10^{-8}

Processes





- DM production is dominated at IR

$$\text{e.g. } \dot{n}_{\tilde{a}} + 3Hn_{\tilde{a}} = \langle \sigma v \rangle n_1 n_2 \sim T^4$$

$$Y_{\tilde{a}} \propto 1/\mu$$

NLSP contribution is dominant

Boltzmann equation

We need momentum distribution for matter power spectrum

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

We derived **general expressions** for collision term (for any mass spectrum)

- 2-to-2 scattering

$$\frac{g_{\tilde{a}}}{E_{\tilde{a}}} C_{1+2\to\tilde{a}+3}(t,p_{\tilde{a}}) = \pm \frac{T}{512\pi^3 p_{\tilde{a}} E_{\tilde{a}}} e^{-E_{\tilde{a}}/T} \int ds \frac{1}{\sqrt{s} p_{3\tilde{a}}} \ln\left(\frac{1 \pm e^{-E_3^-(s)/T}}{1 \pm e^{-E_3^+(s)/T}}\right) \int dt \sum_{\text{spin}} |\mathcal{M}_{1+2\to\tilde{a}+3}|^2 \,,$$

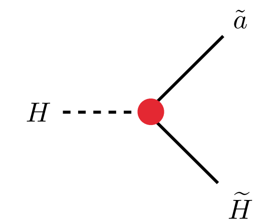
- 3-body decay

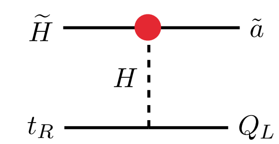
$$\frac{g_{\tilde{a}}}{E_{\tilde{a}}} C_{1\to\tilde{a}+2+3}(t,p_{\tilde{a}}) = \pm \frac{T}{512\pi^3 p_{\tilde{a}} E_{\tilde{a}}} \int dm_{23}^2 \frac{1}{\sqrt{m_{23}^2} \tilde{p}_{1\tilde{a}}} \ln\left(\frac{1 \pm e^{-E_1^-(m_{23}^2)/T}}{1 \pm e^{-E_1^+(m_{23}^2)/T}}\right) \int dm_{2\tilde{a}}^2 \sum_{\text{spin}} |\mathcal{M}_{1\to\tilde{a}+2+3}|^2 \,,$$

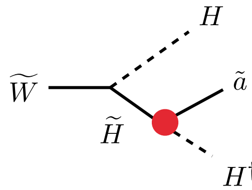
$$f_{\tilde{a}}(t_f,p) = \int_{t_i}^{t_f} dt \frac{1}{E_{\tilde{a}}} C\left(t, \frac{a(t_f)}{a(t)} p\right)$$

Result 1: channel dependence

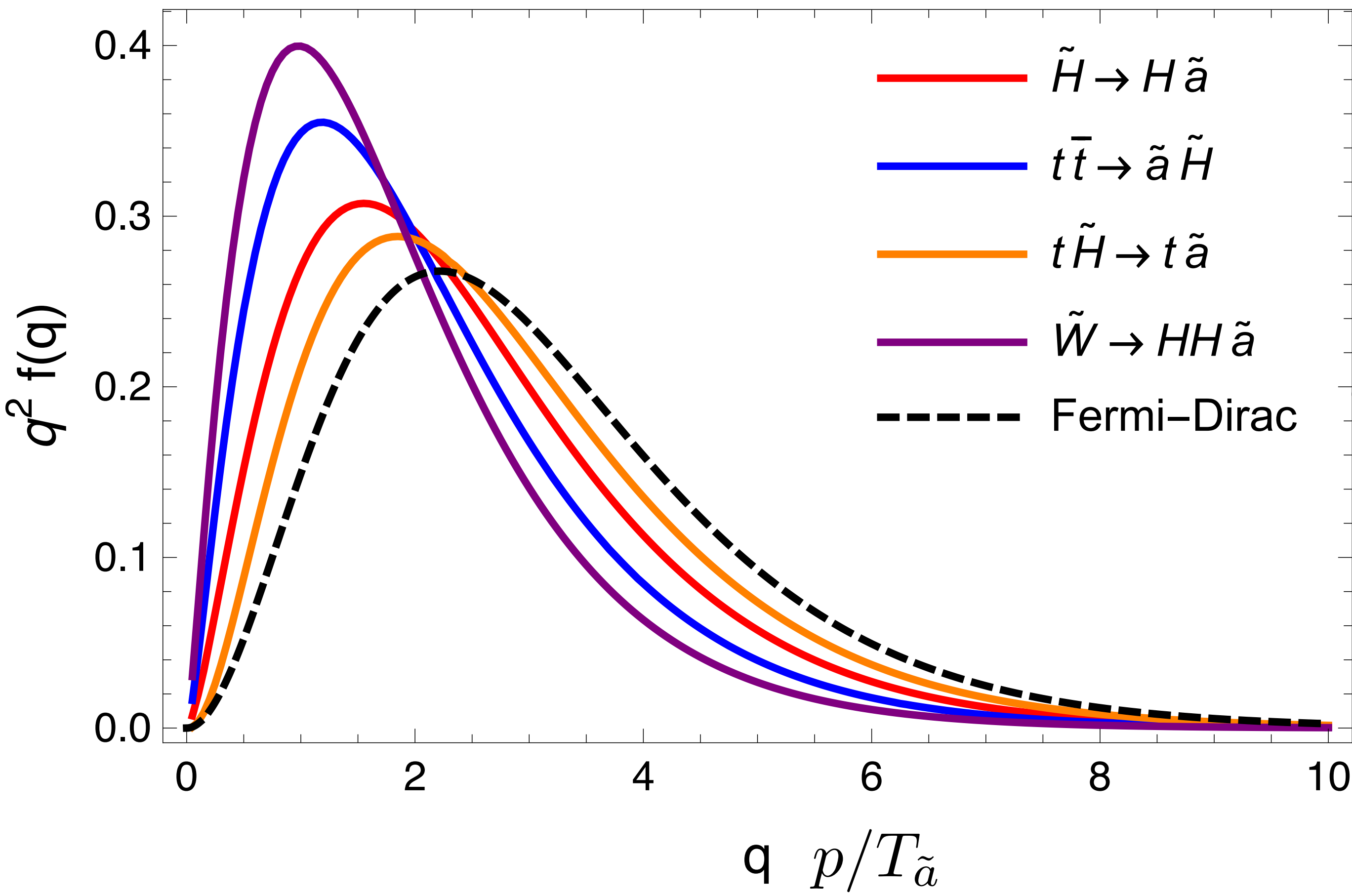
7 keV axino distribution & matter power spectrum

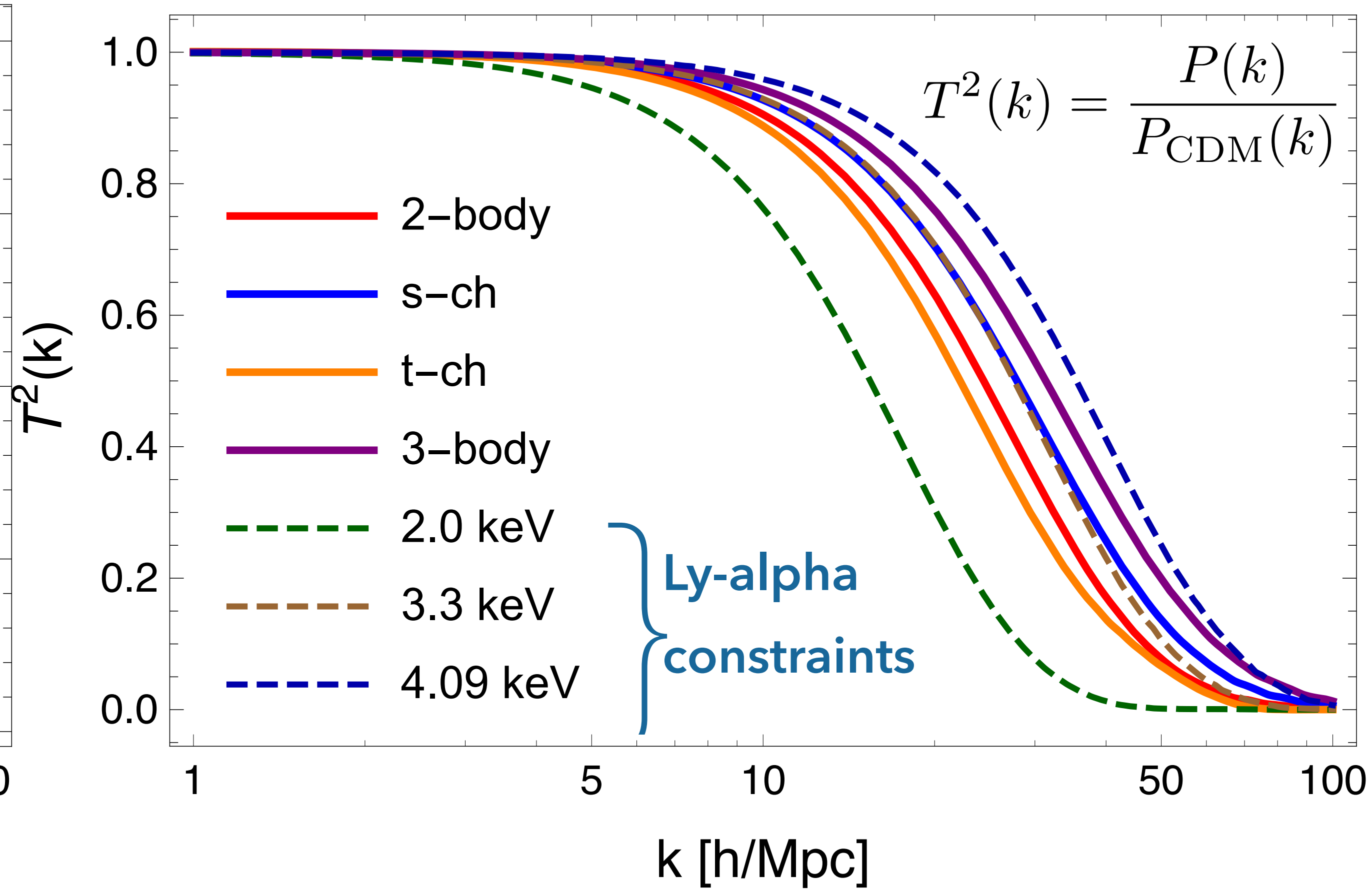






- Freeze-in distributions are **colder** than Fermi-Dirac distribution

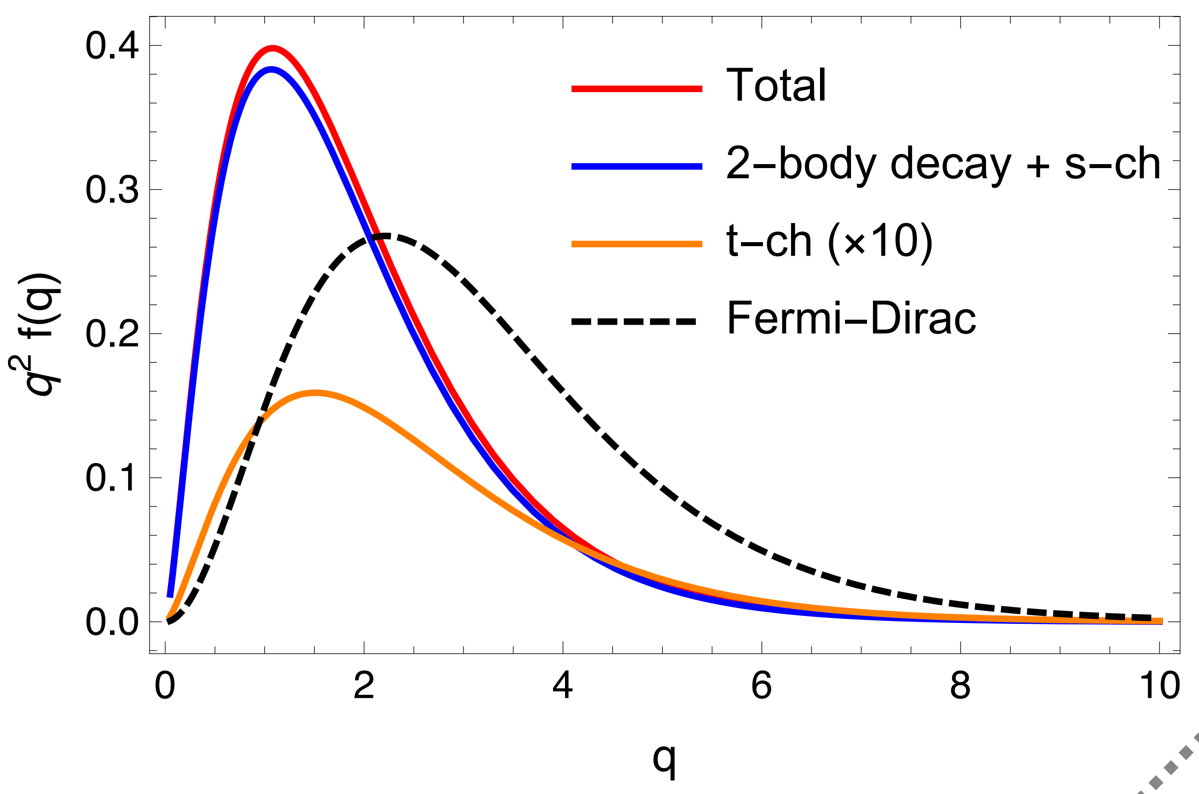


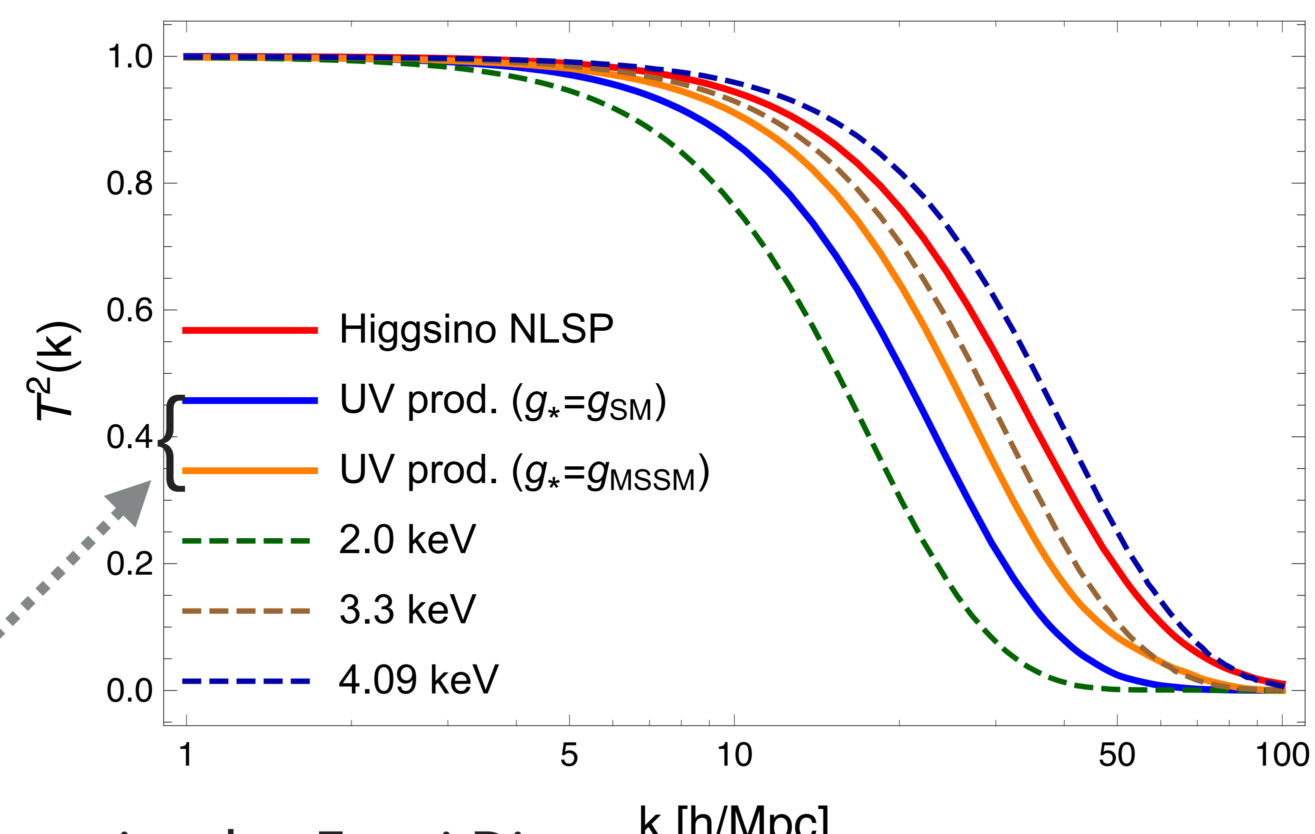


- But the $m_{\rm WDM}$ > 4.09 keV constraint disfavors 7 keV axino
- "$m_{\rm WDM}$ > 4.09 keV" assumes a model of very low $T_{\rm DM}$ ($g_* \sim 7000$) $T_{\rm DM} = \left(\frac{g_*(T)}{g_*(T_{\rm dec})}\right)^{1/3} T$

Result 2: a realistic model

- Axino distribution in a realistic model is ***superposition*** of several processes
- We take a benchmark point, Higgsino NLSP:
  - **Higgsino: 500 GeV, H_u: 1 TeV**, axino: 7 keV, other SUSY particles are heavier





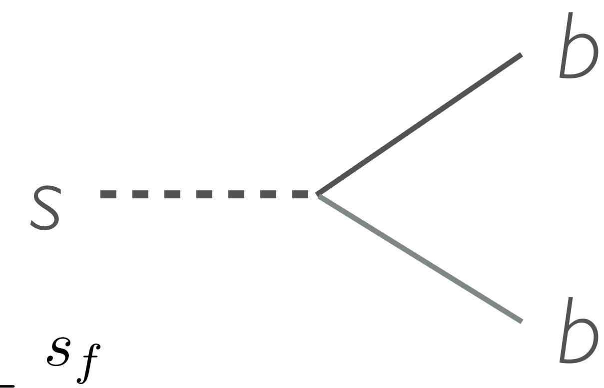
distribution proportional to Fermi-Dirac

7 keV axino DM has tensions with the Lyman-alpha observations

How to evade Ly-alpha constraint?

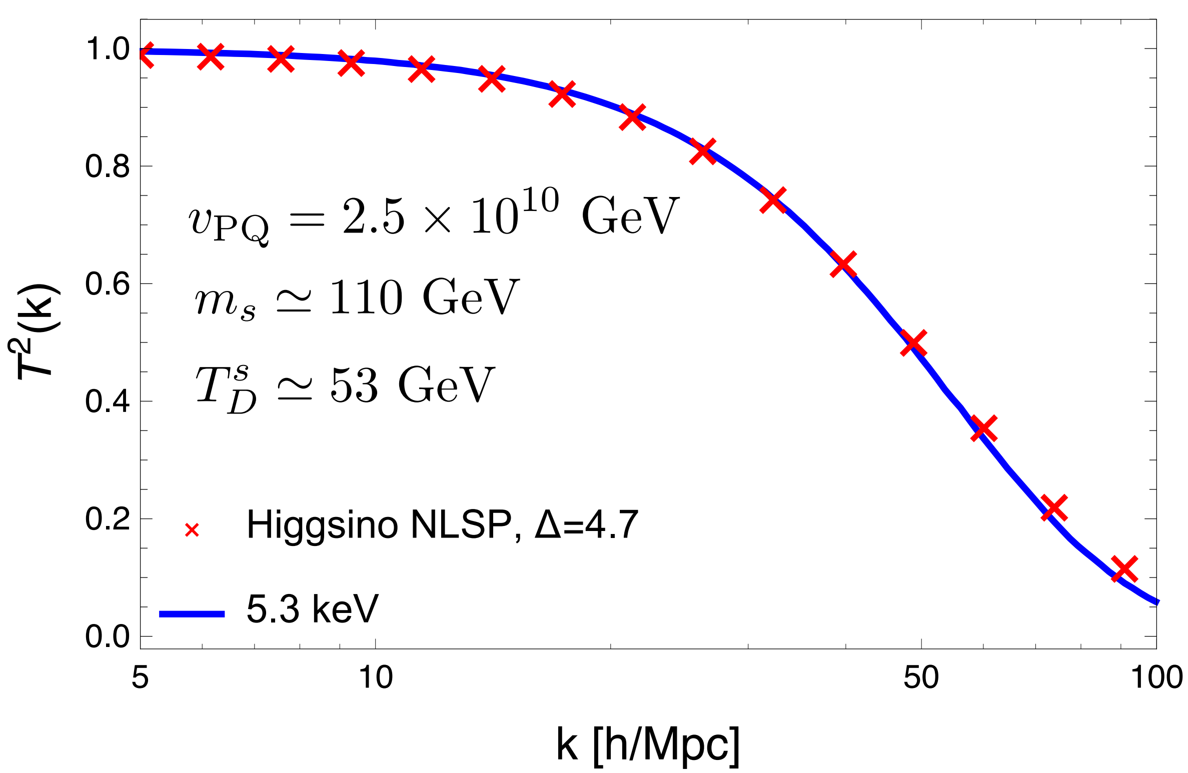
- Entropy production

One way is to **decrease temperature** of axino



- Axino model necessarily contains **saxion**
- Saxion decay **after** axino production injects entropy $\Delta = \frac{s_f}{s_i}$

$$T_{\tilde{a}} \to T_{\tilde{a}} \Delta^{-1/3}$$



- With Δ=4.7, the current strongest constraint $m_{\rm WDM}$ > 5.3 keV is evaded!

- DM abundance is also explained!

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

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

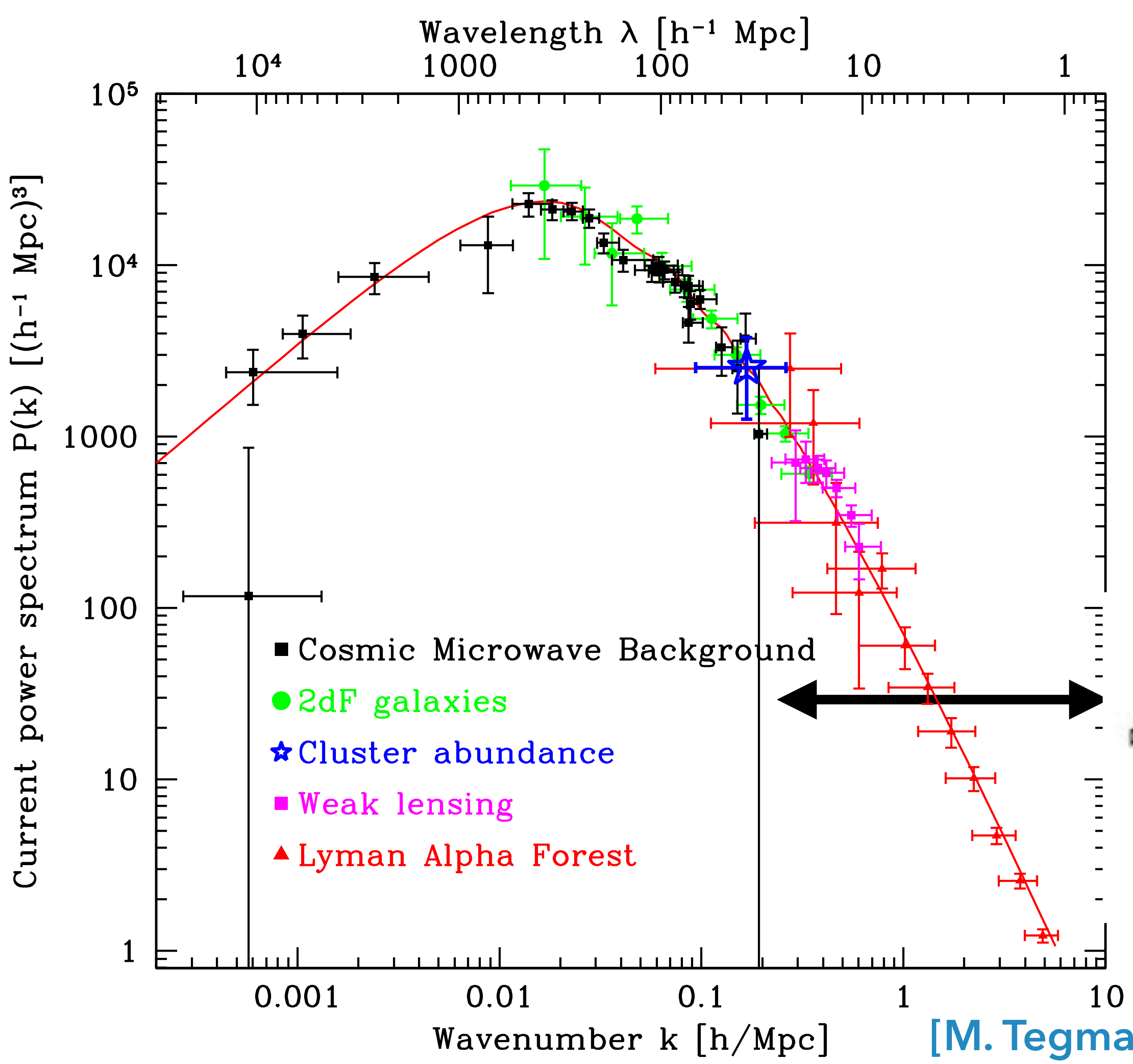
Backup

Matter power spectrum & Ly-alpha forest

- Matter distribution is calculated by cosmological perturbation theory

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

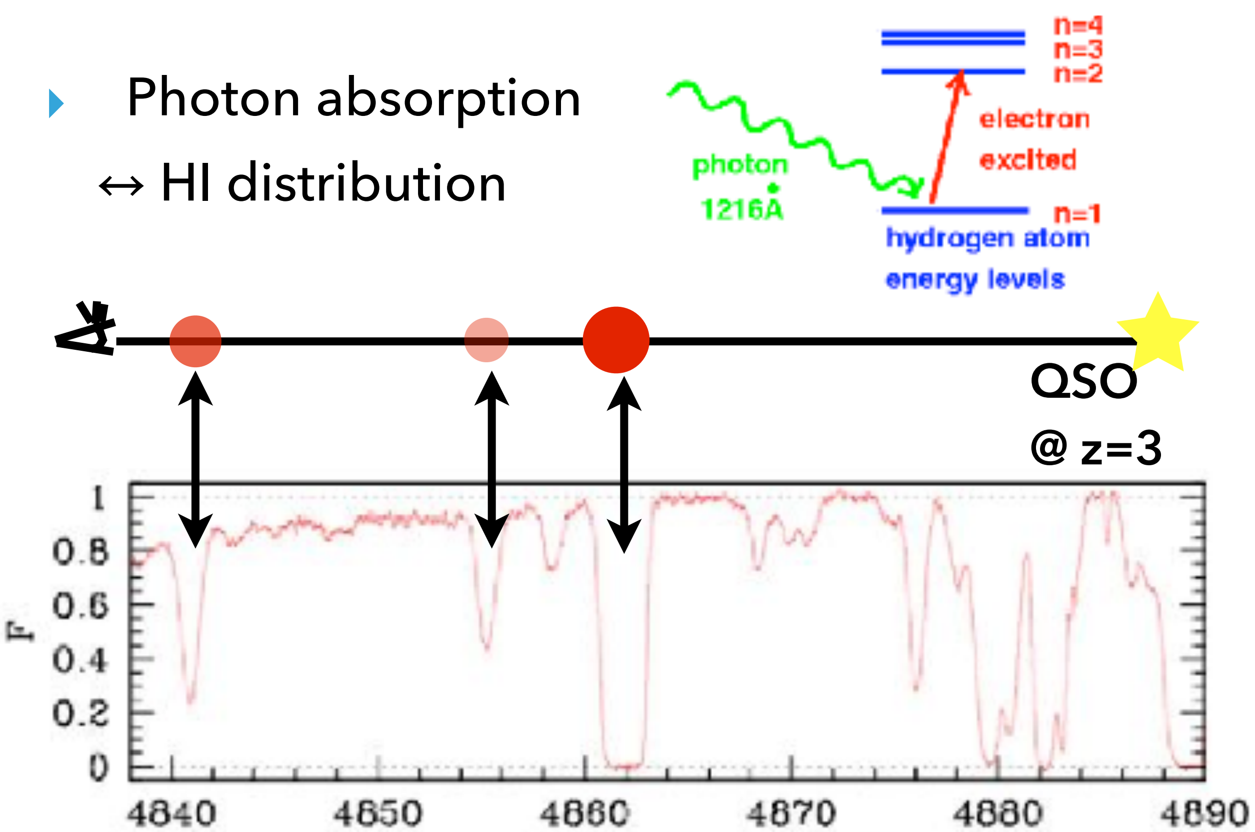
- Observable quantity is **matter power spectrum**



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

- Photon absorption

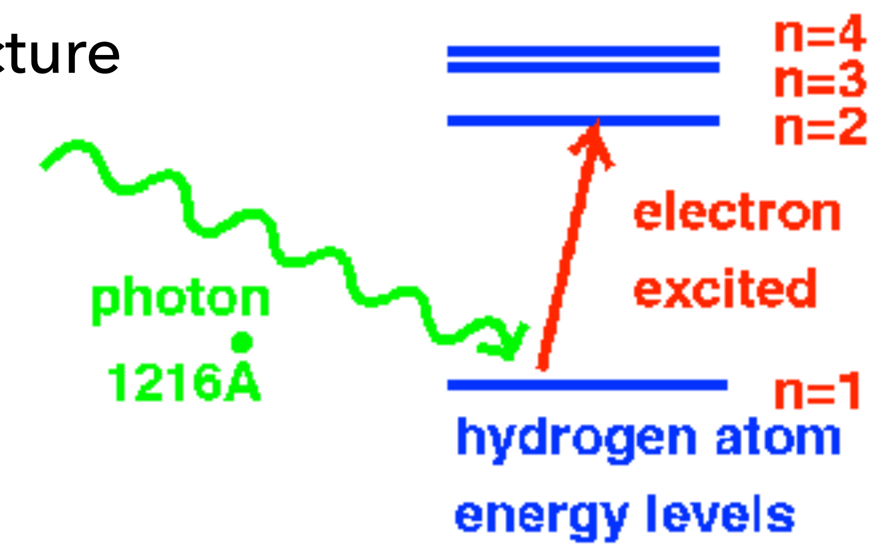
↔ HI distribution

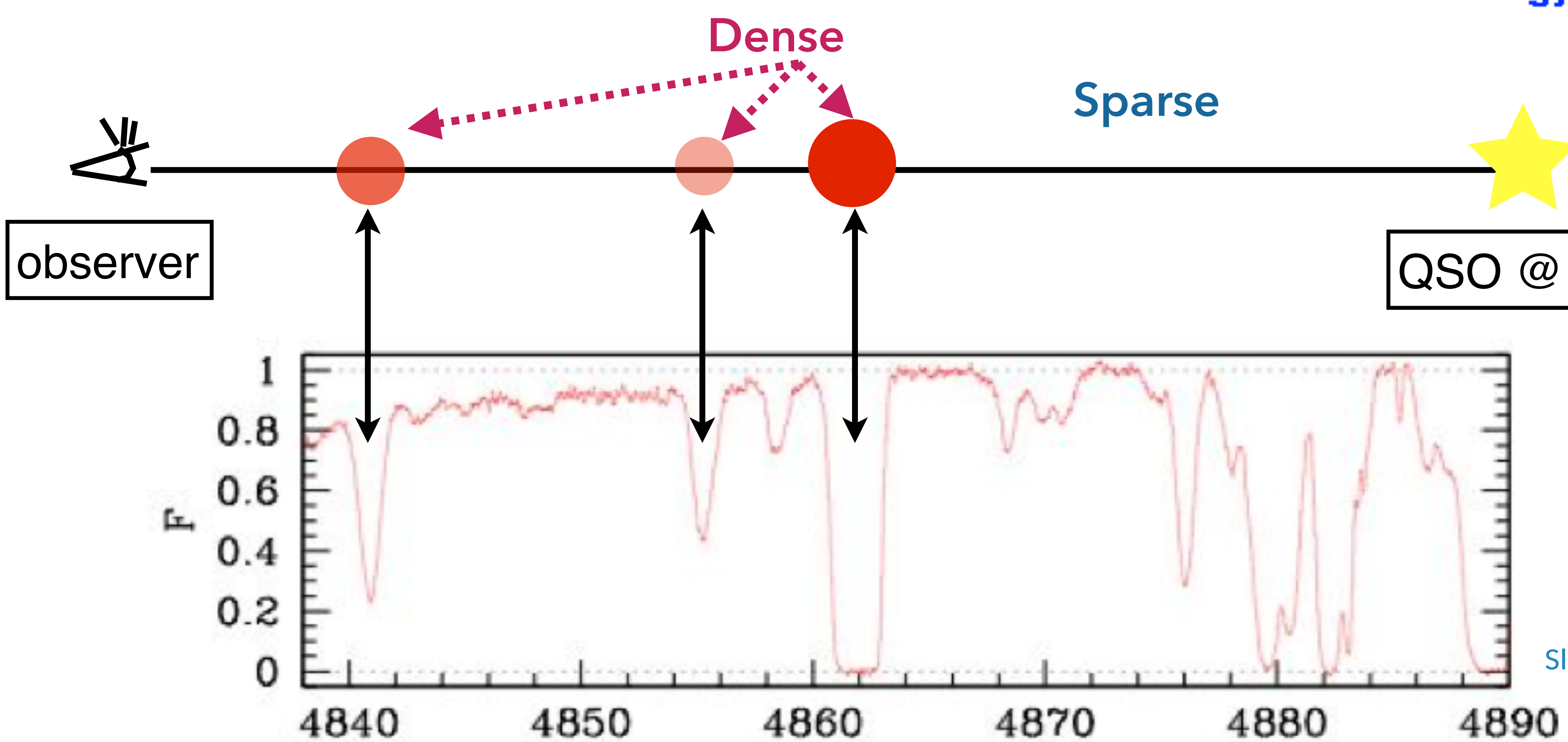


[M. Tegmark & M. Zaldarriaga (2002)]

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

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

- Mass bounds 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)]

Axino in SUSY DFSZ model

- As a benchmark model, we take DESZ axion model
  - Superpotential

PQ= -1, +1, +1

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

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

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

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:
  - $v_{\rm PQ} \gtrsim 10^9\ {\rm GeV} \qquad M_* \sim 10^{16}\ {\rm GeV}$
  - μ term: $\mu \sim \dfrac{y_0 v_{\rm PQ}^2}{2M_*}$
  - Axino-Higgs-Higgsino interaction: $\dfrac{2\mu}{v_{\rm PQ}} \sim 10^{-8}$
- Small R-parity violation explains 3.5 keV excess (See K. J. Bae's talk)

R-parity violating decay of axino

- Bilinear R-parity violation is introduced

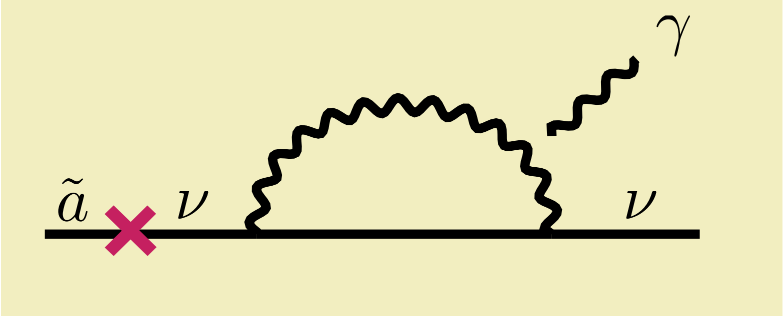
PQ= -1, +2, +1

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

- 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



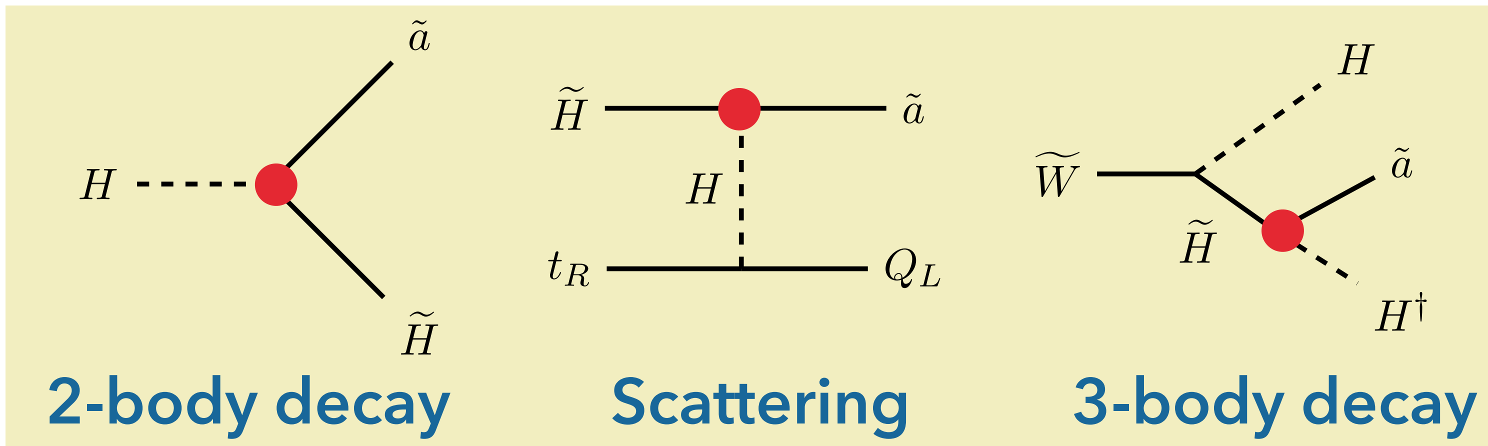
$\sin^2 2\theta \sim 10^{-10}$ explains 3.5 keV excess!

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

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}**

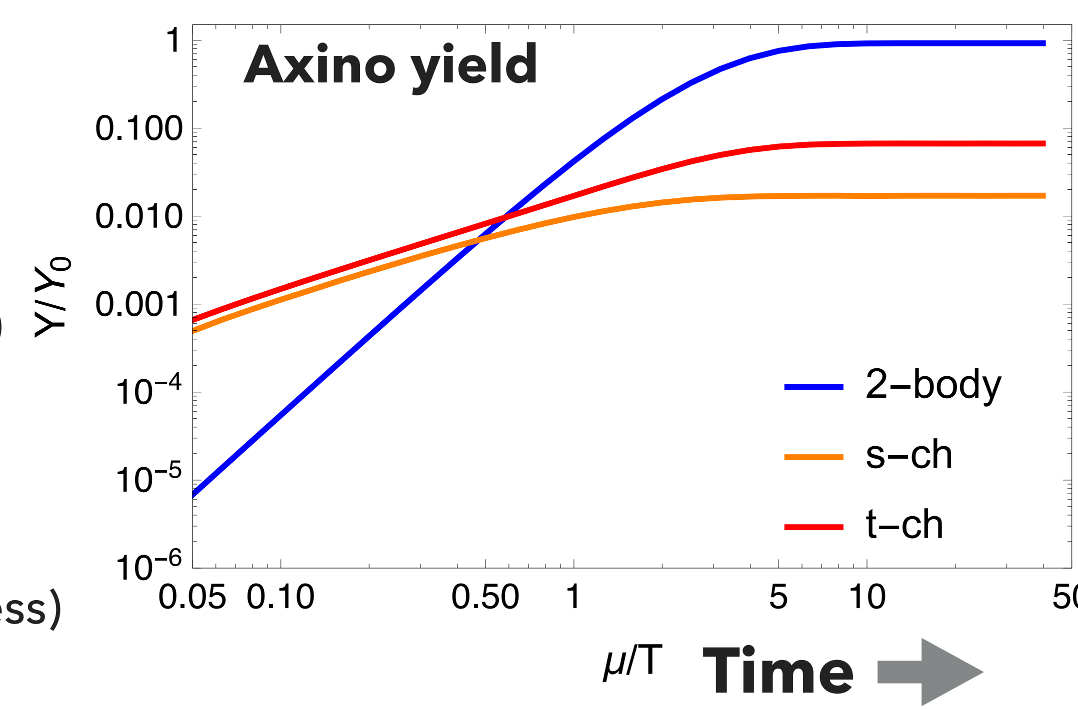
- For instance, Boltzmann equation for scattering

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

- 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 $f_{\tilde{a}} \simeq 0$

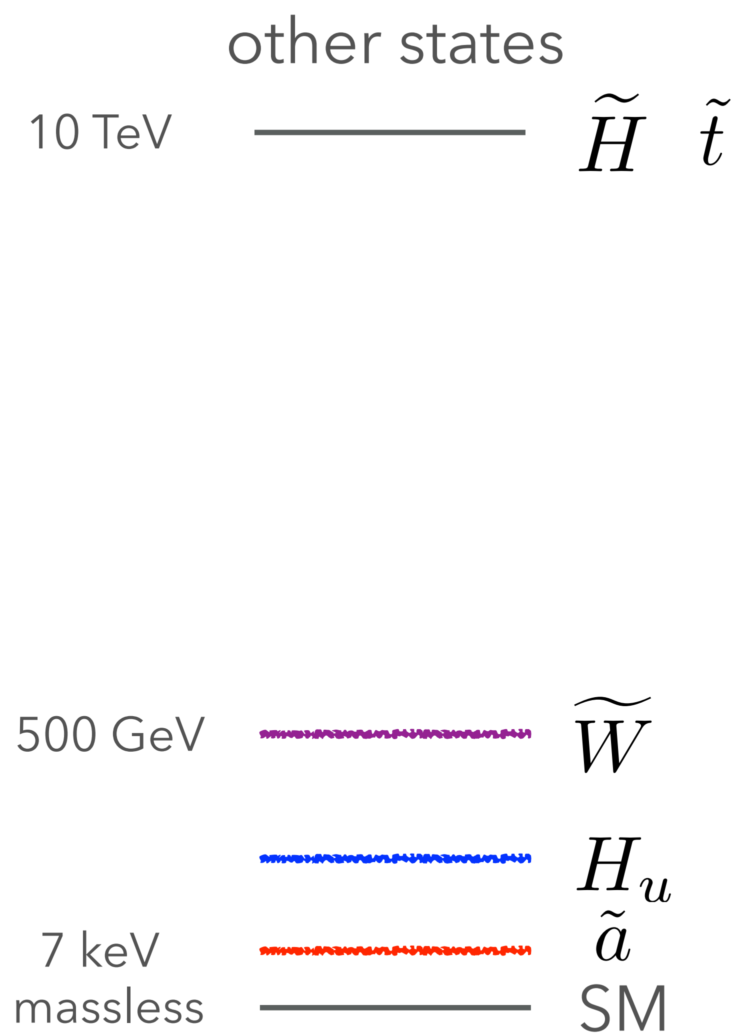
$$\frac{g_{\tilde{a}}}{E_{\tilde{a}}} C_{1+2+\cdots\to\tilde{a}+3+4+\cdots}(t,p_{\tilde{a}}) = \frac{1}{2E_{\tilde{a}}} \int \prod_{I\neq\tilde{a}} \frac{d^3p_I}{(2\pi)^3 2E_I} (2\pi)^4 \delta^4(\hat{p}_1 + \hat{p}_2 + \cdots - \hat{p}_{\tilde{a}} - \hat{p}_3 - \hat{p}_4 - \cdots)$$
$$\times \sum_{\text{spin}}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

- Integrating Boltzmann Eq., we obtain phase space distribution

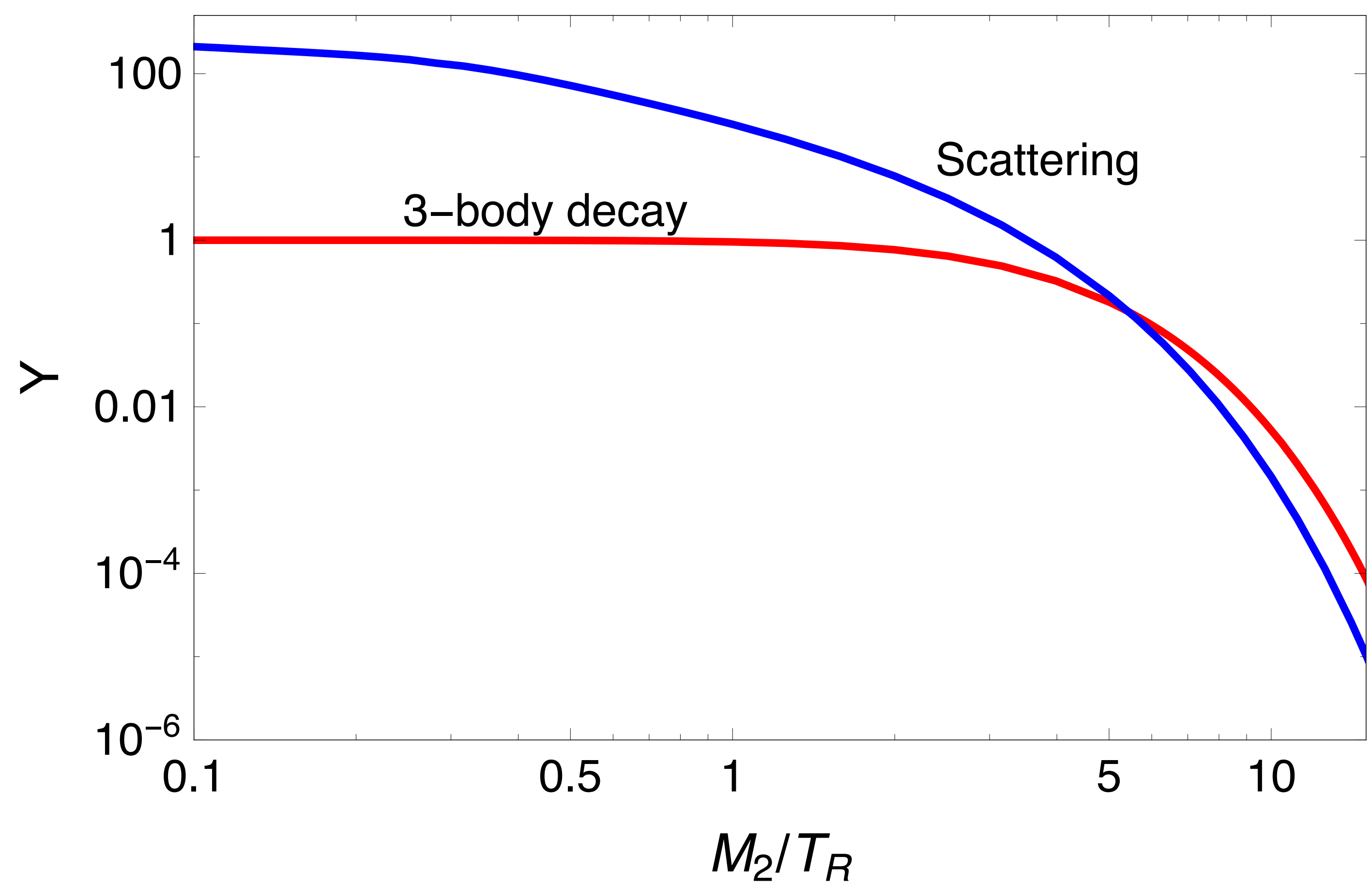
$$f_{\tilde{a}}(t_f,p) = \int_{t_i}^{t_f} dt \frac{1}{E_{\tilde{a}}} C\left(t, \frac{a(t_f)}{a(t)} p\right)$$

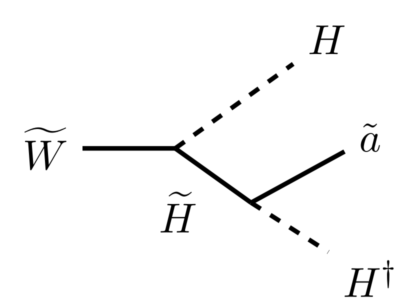
Another benchmark

Wino NLSP



3-body decay vs. scattering





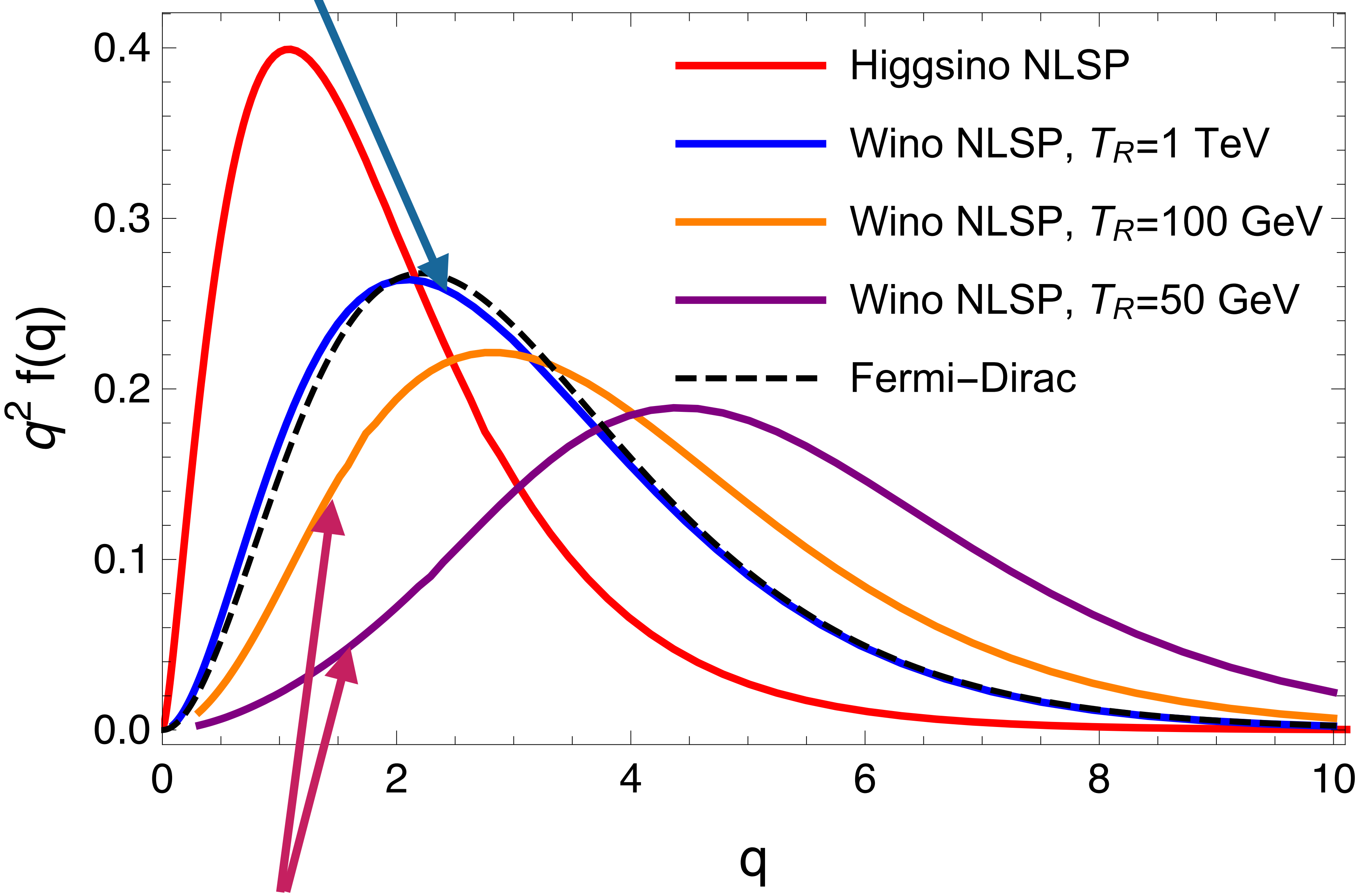
= dim. 5

→ 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

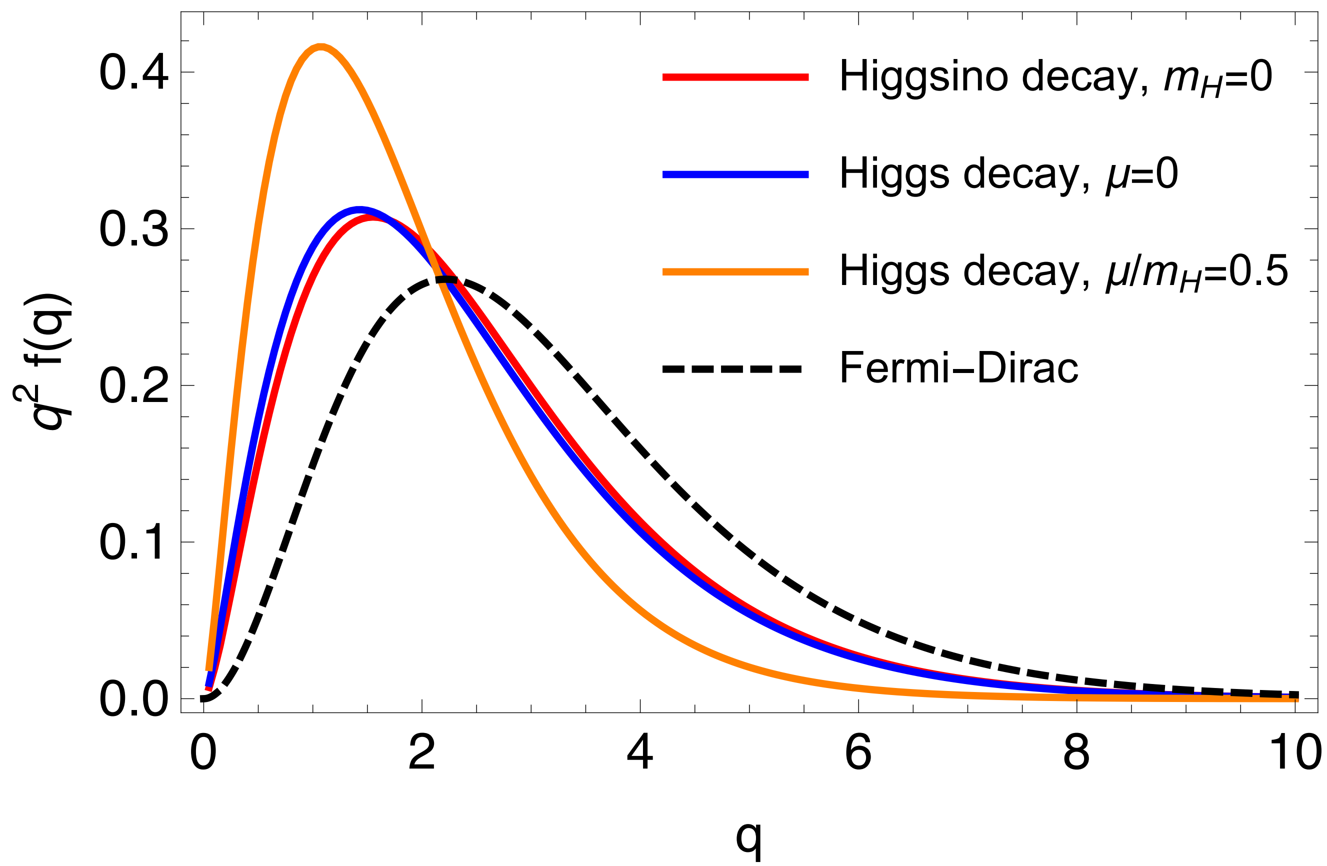


3-body decay dominant, but **hotter** than thermal one

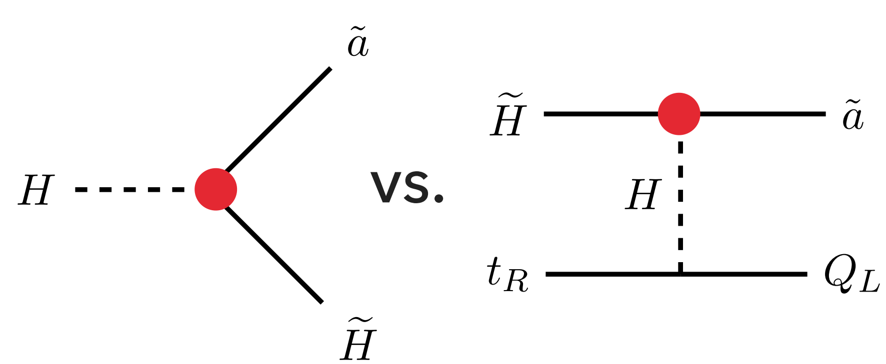
$T_R < M_2/5$ implies axino energy ($\sim M_2/3$) is larger than temperature

How to evade Ly-alpha constraint?

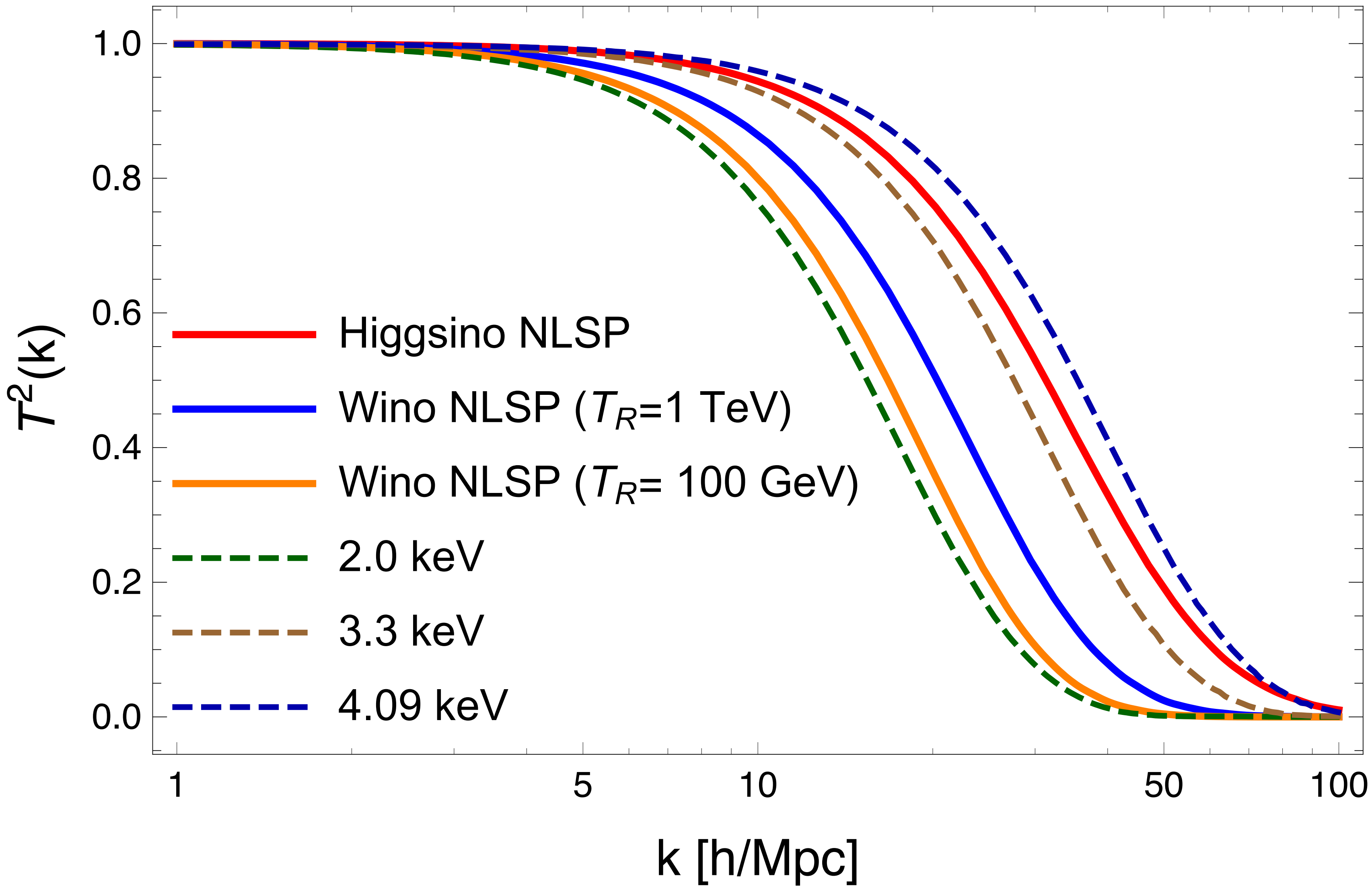
- Mass degeneracy



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



Another benchmark

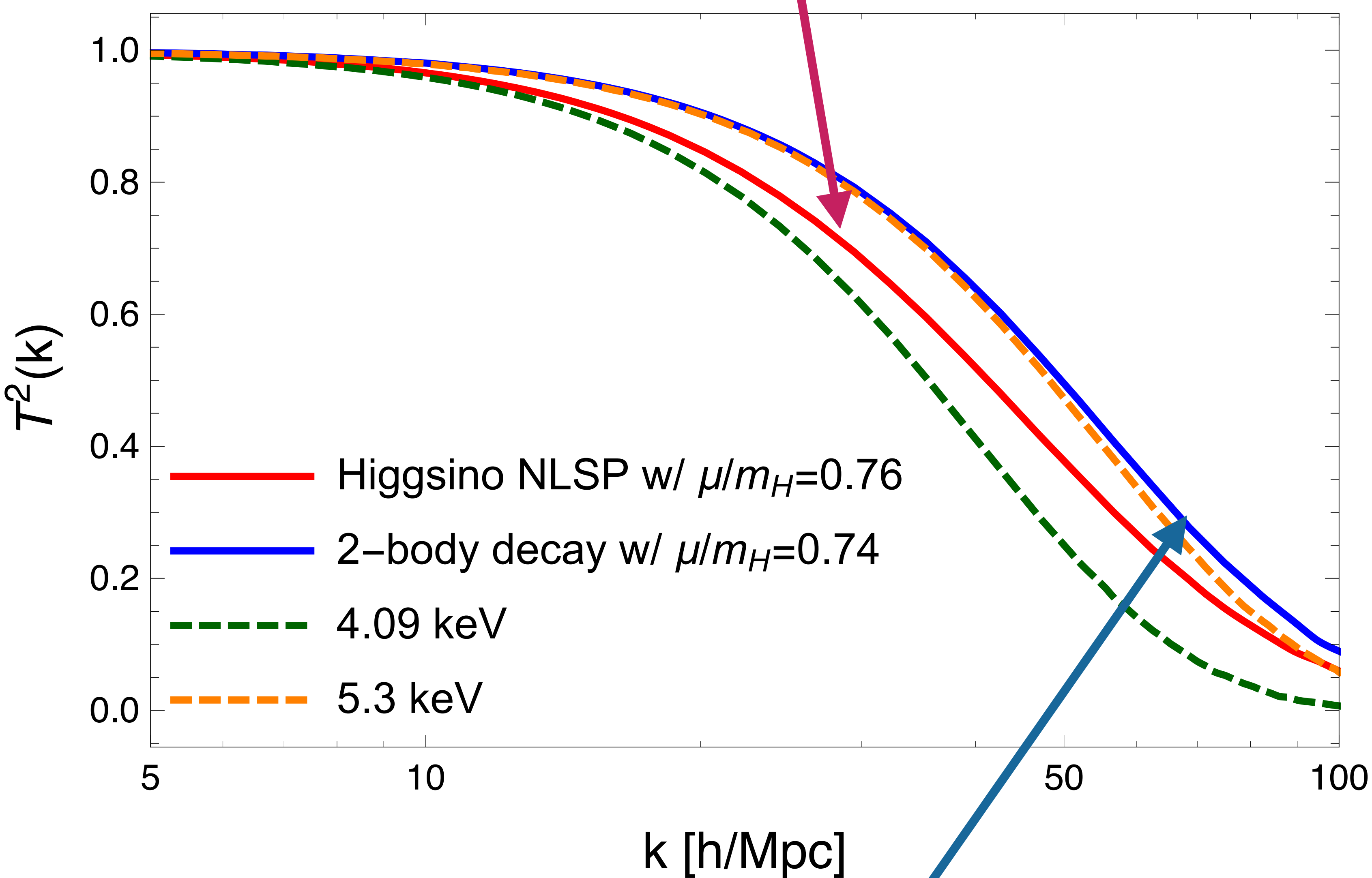


- Wino NLSP cases are disfavored by m_{WDM} > 3.3 keV

How to evade Ly-alpha constraint?

- Mass degeneracy

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

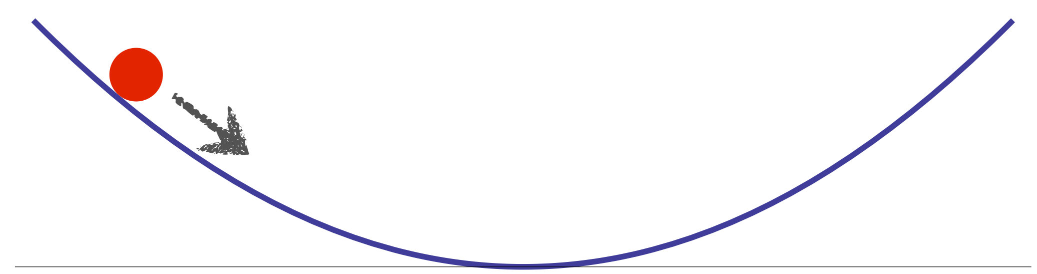


If only 2-body decay exists, m_{WDM} > 5.3 keV can be evaded

How to evade Ly-alpha constraint?

- Entropy production

- One way is to **decrease temperature** of axino



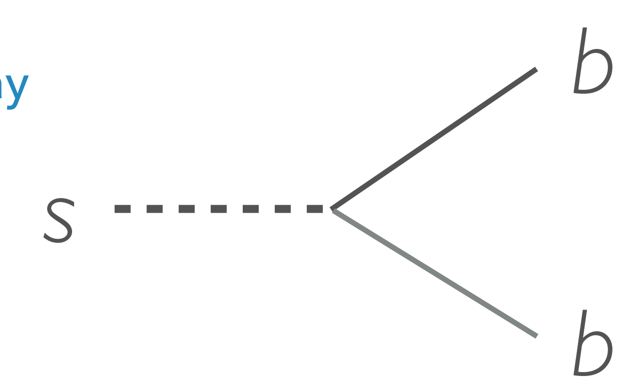
- Saxion is produced by coherent oscillation

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

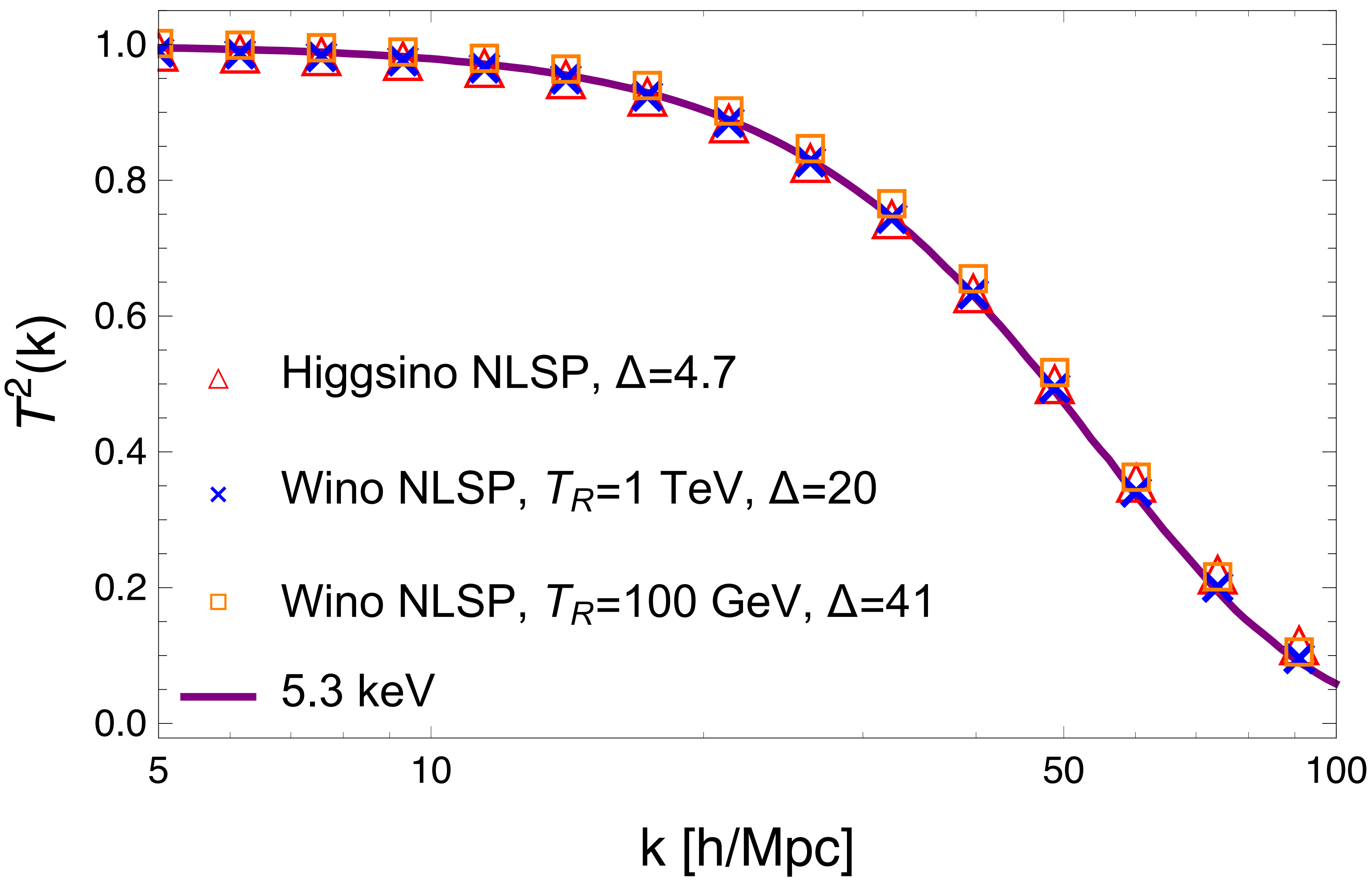
- At some later time, saxion dominates the universe

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

- 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 $T_{\tilde a} \to T_{\tilde a} \Delta^{-1/3}$



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