FREEZE-IN AXINO

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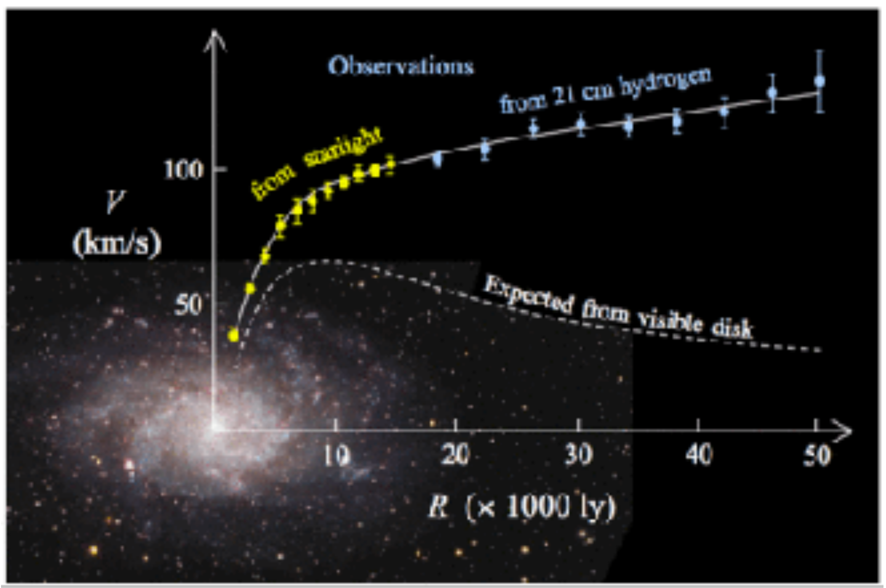
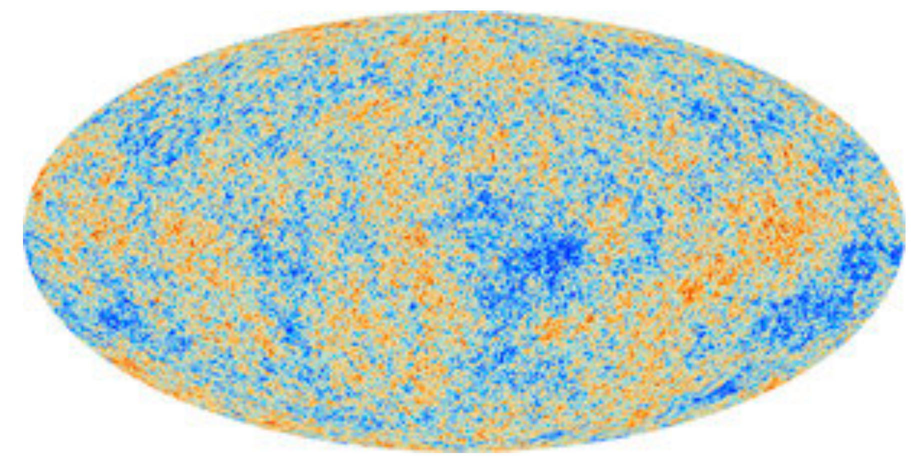
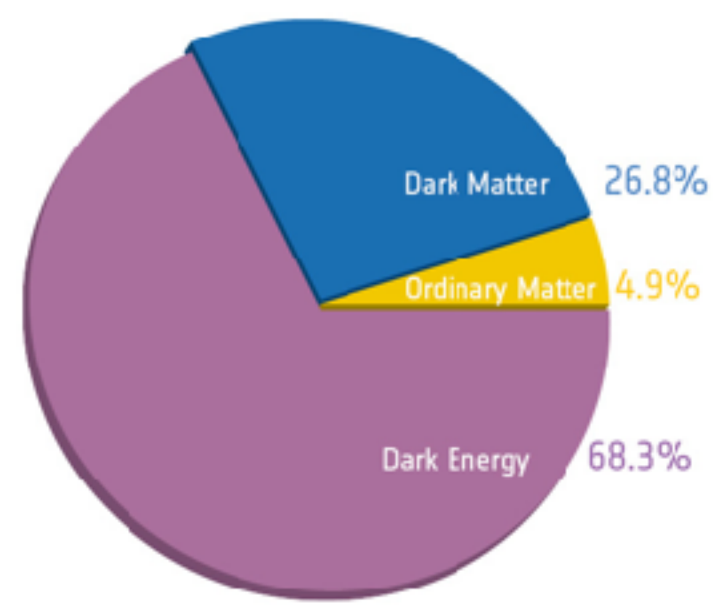
DARK MATTER

- Universe is filled with something unknown, which is called "Dark Matter."
- Observational evidences are





- DM density is ~1/4 of the energy of the Universe.
- All the evidences are gravitational. We do not know any non-gravitational interactions.

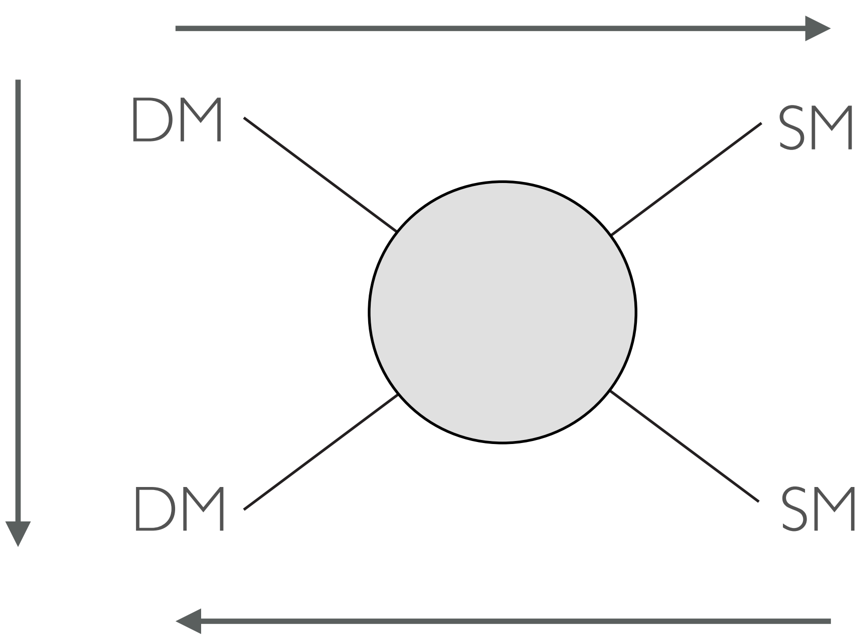


WIMP "MIRACLE"

- **Weakly Interacting Massive Particle**

  DM is gravitationally observed: non-luminous, non-baryonic, Cold

  ➡ *Weakly Interacting* new particle



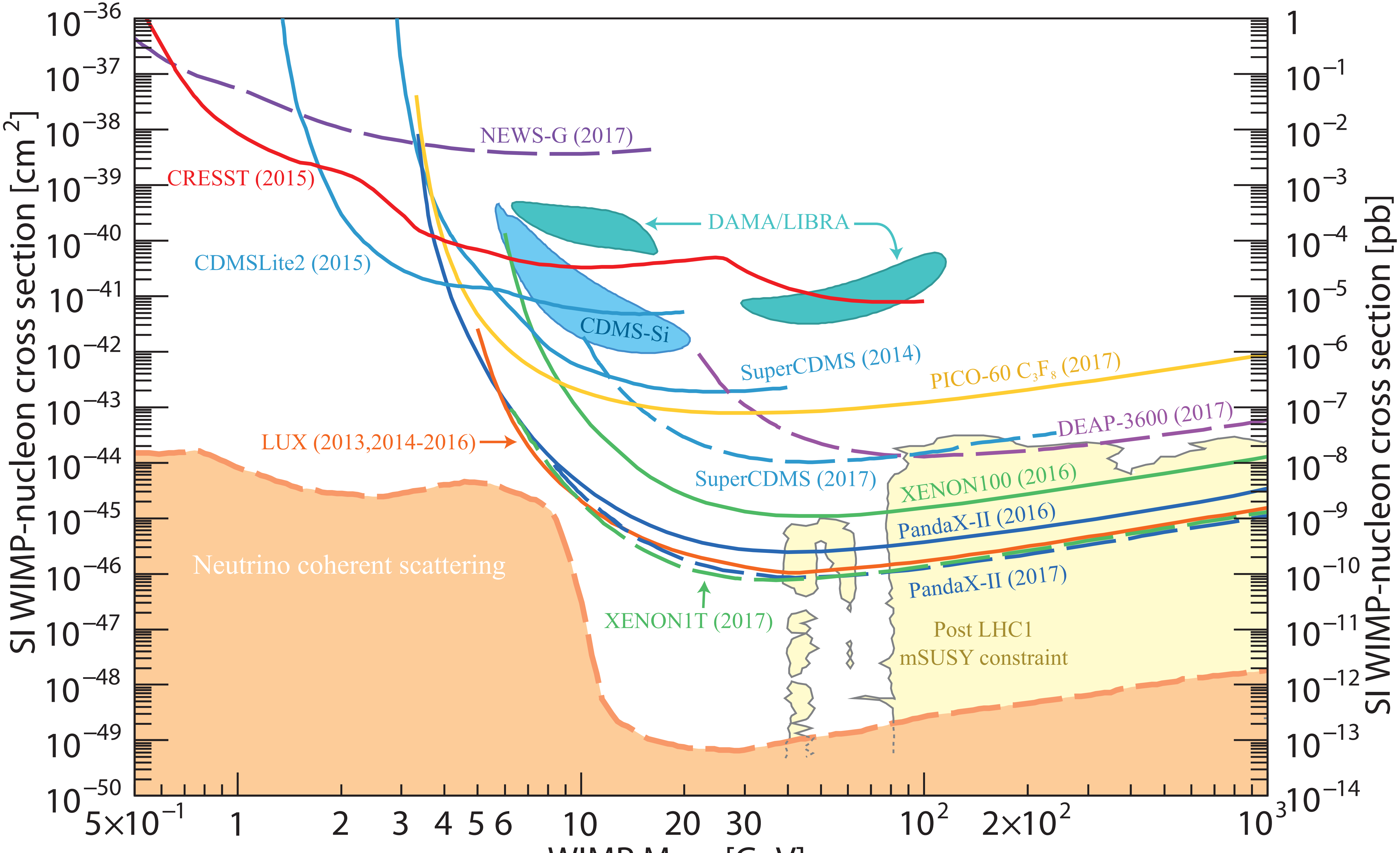
$$\Omega_\chi h^2 \sim 0.1 \left(\frac{3 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}}{\langle \sigma_A v \rangle} \right)$$

$$\langle \sigma v \rangle \sim \frac{\alpha_W^2}{(\mathrm{TeV})^2}$$

- Detection possibility

$$\sigma_N \sim \frac{G_F^2 m_N^2}{\pi} \sim 10^{-39}\ \mathrm{cm}^2$$

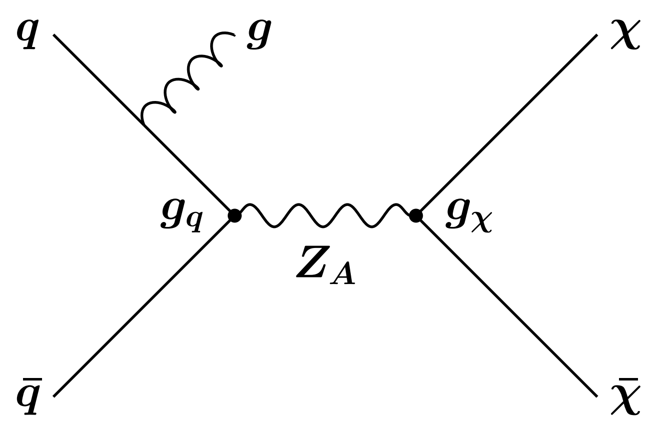
WIMP SEARCH

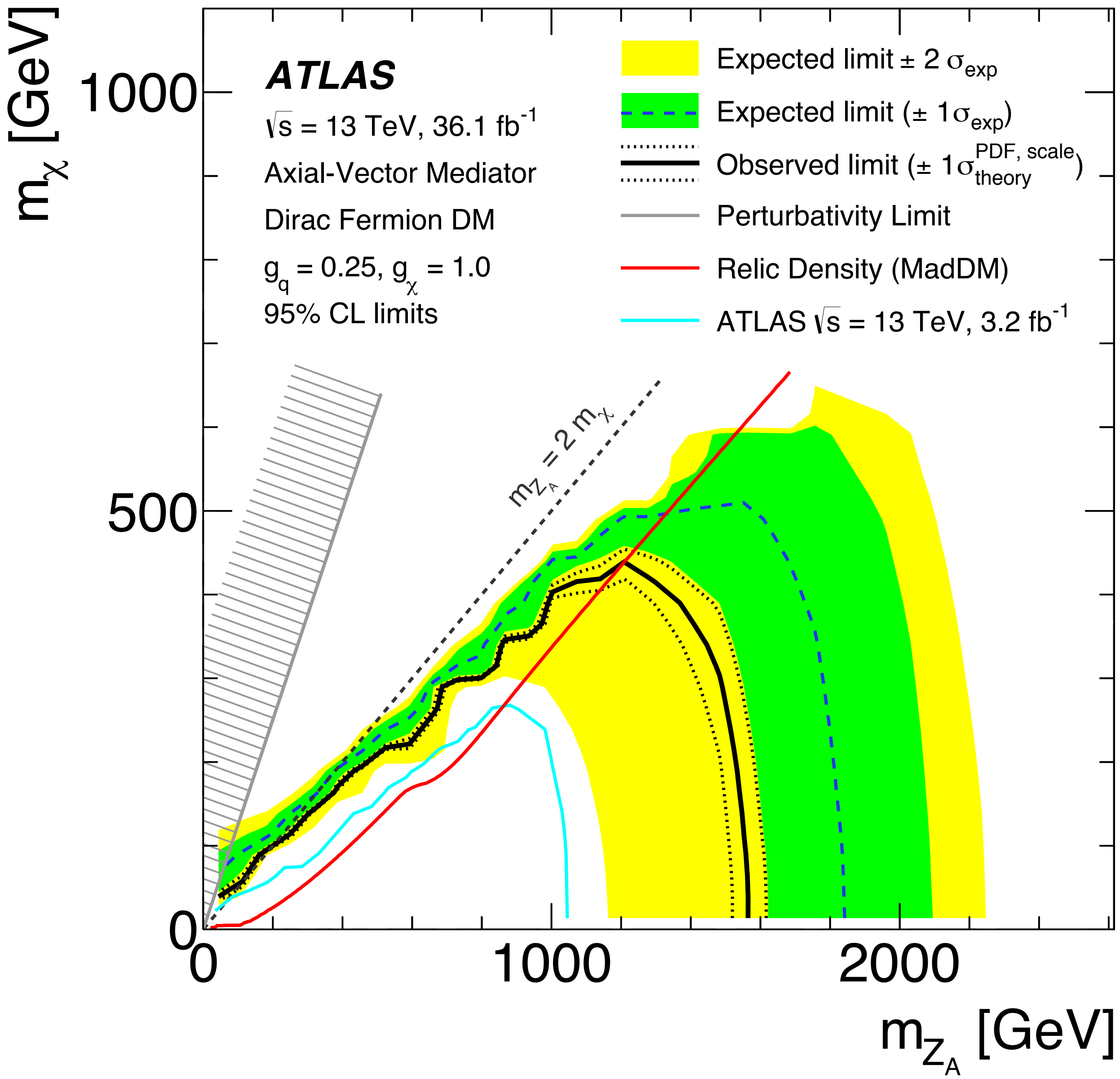


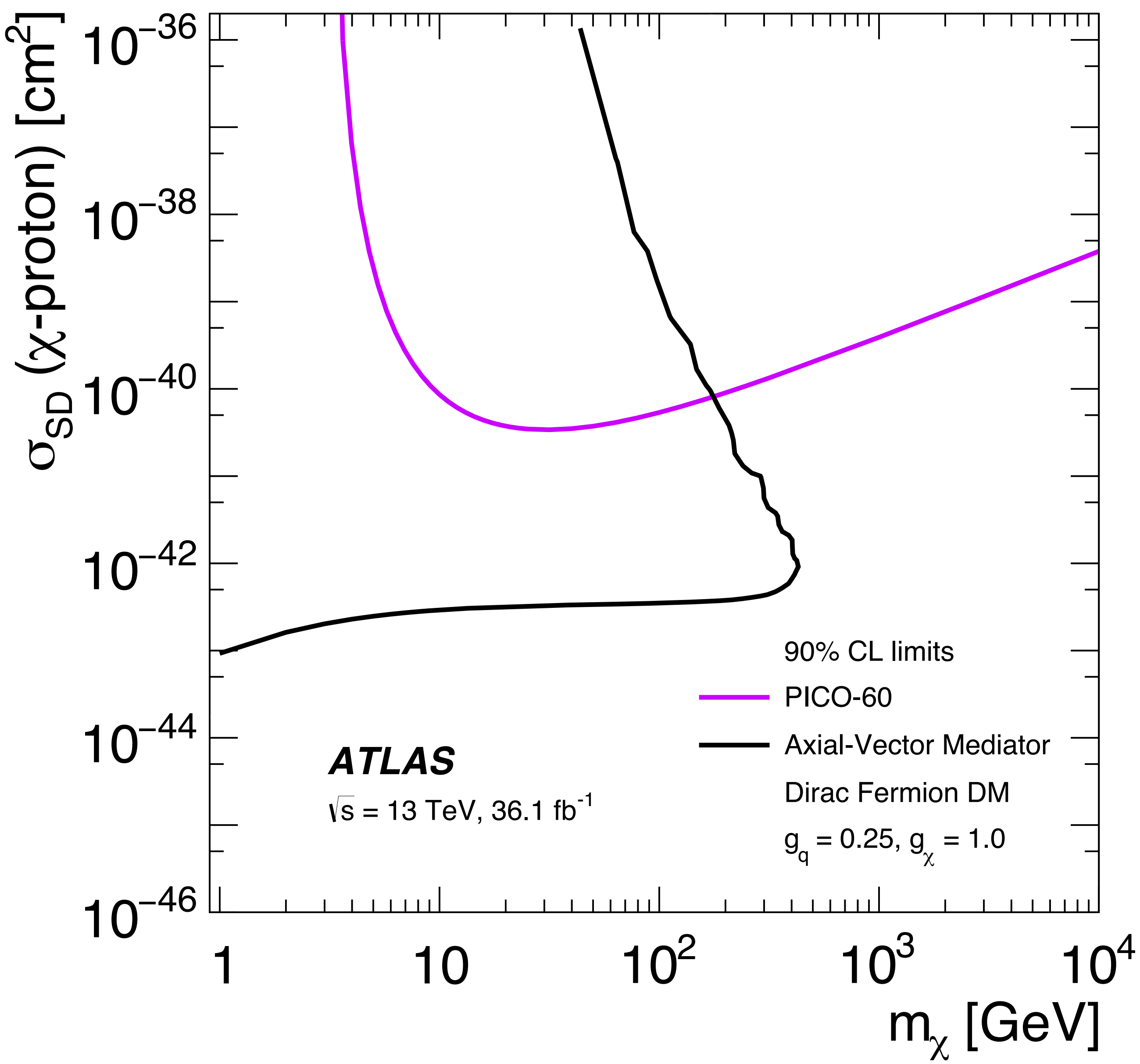
PDG (2018)

WIMP SEARCH

1711.03301 (ATLAS)







ALTERNATIVE TO WIMP

- **DM may not be WIMP...**

Non-WIMP (or non-thermal) DM

e.g. gravitino: UV production; depends on inflation, reheating

Feebly Interacting Massive Particle:

IR production: renormalizable coupling, NOT depend on early cosmology

→ abundance vs. model params

phase space distribution vs. small scale structure

e.g. Lyman-alpha forest data

- **Freeze-in Axino**

FIMP in SUSY+Axion: natural feebly interaction

OUTLINE

1. Introduction
2. Freeze-out vs. Freeze-in
3. Freeze-in Axino in DFSZ model
4. "Cold" light axino dark matter
5. Conclusions

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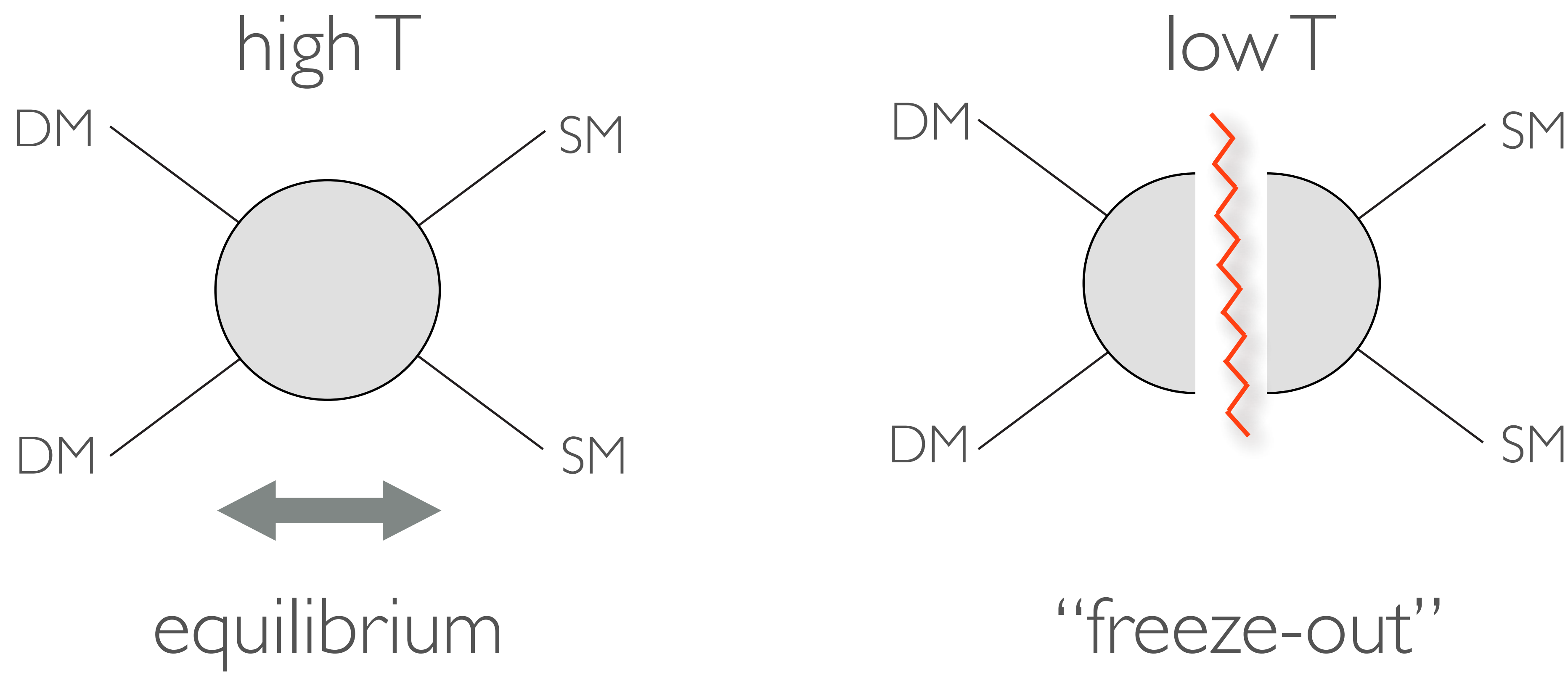
FREEZE-OUT

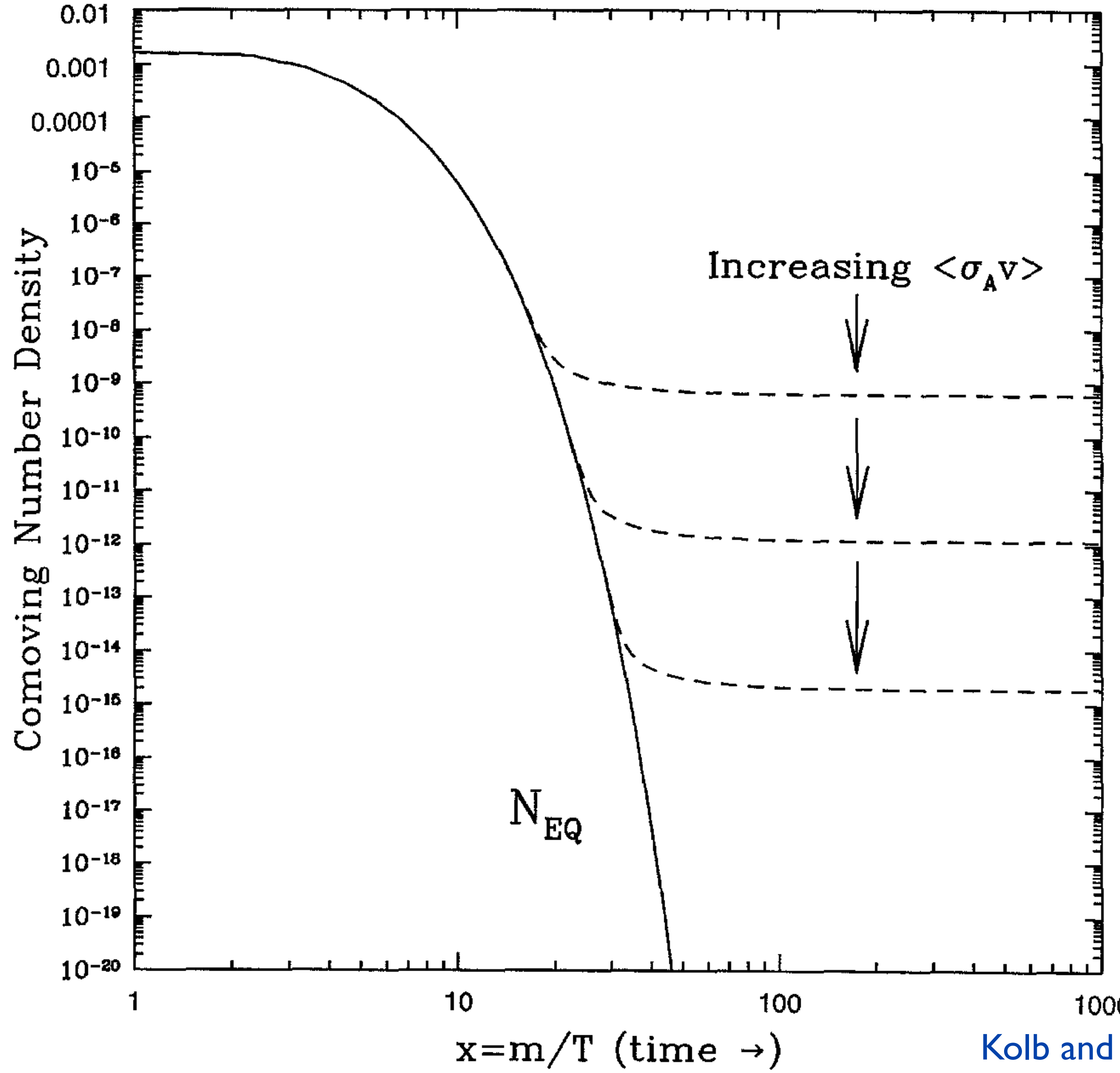
Thermal production of WIMPs:

Start from thermal equilibrium due to O(weak) coupling

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_A v\rangle\left[(n_\chi)^2 - \left(n_\chi^{\mathrm{eq}}\right)^2\right]$$



$$\Omega_\chi h^2 \simeq \frac{3\times 10^{-27}\ \mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_A v\rangle}$$



Kolb and Turner

- Larger $\langle \sigma_A v \rangle$, smaller DM abundance

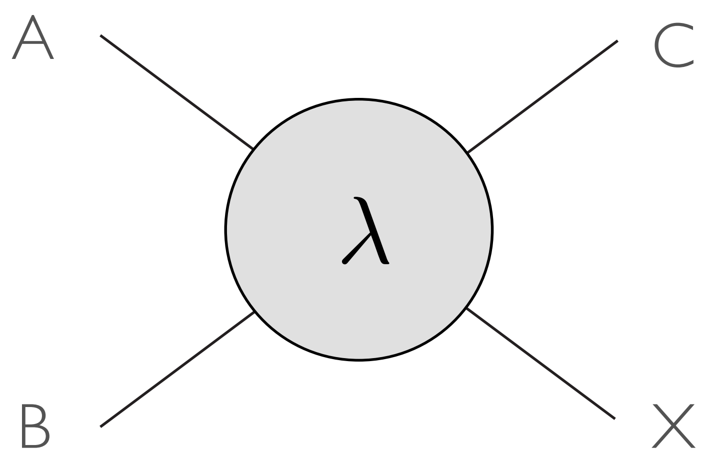
- Weakly interacting particle, $\langle \sigma_A v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$, explains DM abundance

FREEZE-IN

Hall, Jedamzik, March-Russell, West (2009)

Feebly Interacting Massive Particle

$$A + B \to C + X : \qquad \frac{dn_X}{dt} + 3Hn_X = \gamma_{AB\to CX}$$



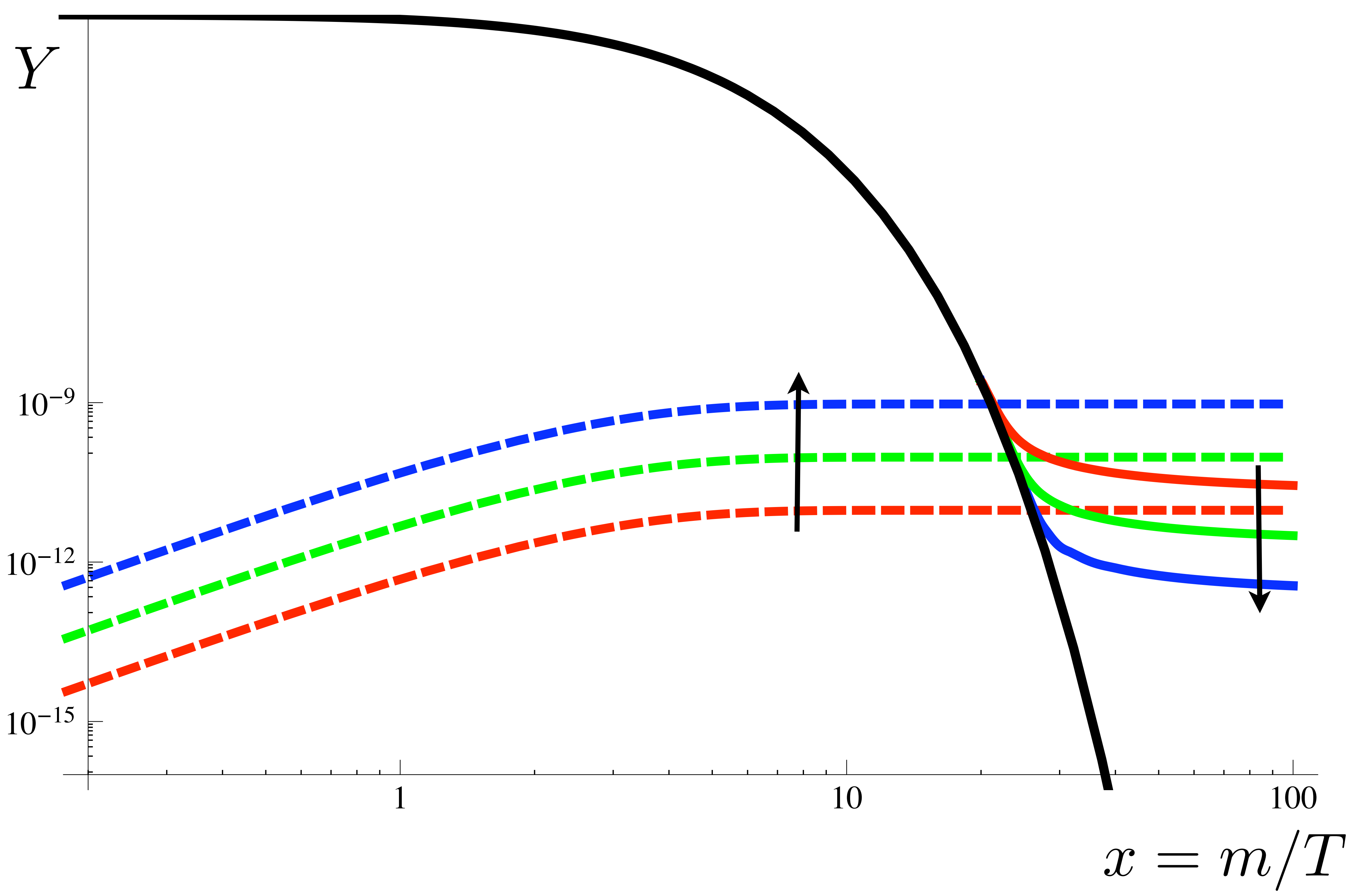
renormalizable coupling

$$|\mathcal{M}|^2 \sim \text{constant} \Rightarrow \sigma \sim \frac{\lambda^2}{T^2}$$

$$Y_X = \frac{n_X}{s} \sim \int_0^{T_R} dT \frac{\gamma_{AB\to CX}}{sH(t)T} \propto \lambda^2$$

Indepedent of T_R

FREEZE-IN



Hall, Jedamzik, March-Russell, West

FREEZE-OUT VS. FREEZE-IN

Freeze-out	**Freeze-in**
$Y \propto \frac{1}{\lambda^2}$	$Y \propto \lambda^2$
produced from equilibrium	non-equilibrium
O(weak) coupling	feeble coupling
$\Downarrow$	$\Downarrow$
(in)direct detection	late decay
thermal distribution	non-thermal distribution

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Topic of this talk!

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3. **Freeze-in Axino in DFSZ model**

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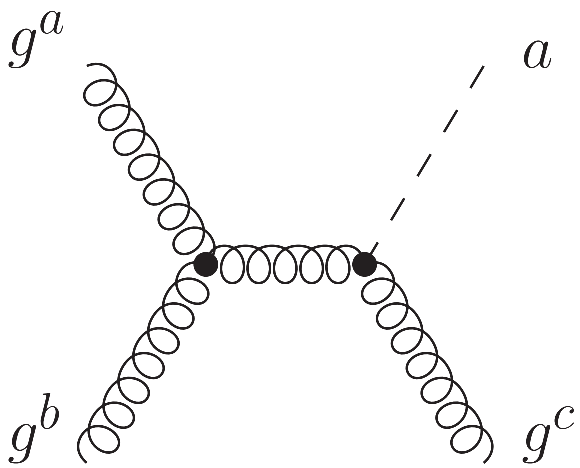
AXION

$$\mathcal{L}_{\rm eff} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a/N}G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} + C_{a\gamma\gamma}\frac{e^2}{16\pi^2}\frac{a}{f_a/N}F^a_{\mu\nu}\widetilde{F}^{a\mu\nu}$$



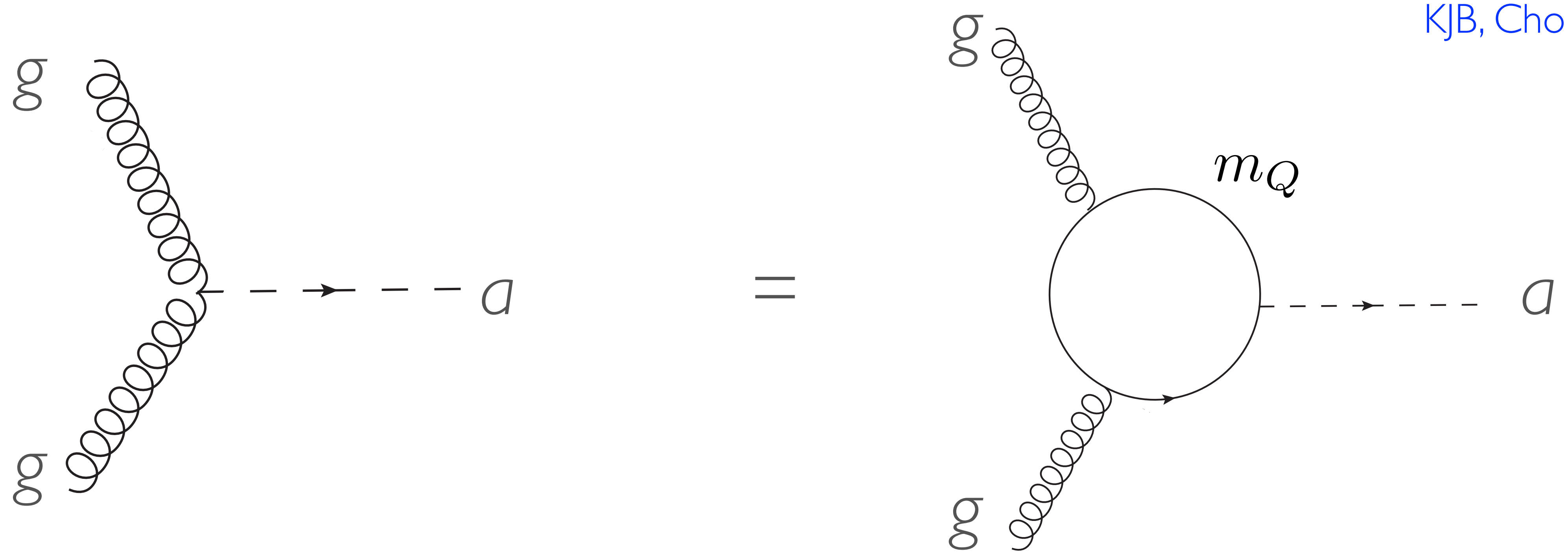
$$|\mathcal{M}|^2 \sim \frac{T^2}{f_a^2}$$

UV production

Graf, Steffen

AXION INTERACTION

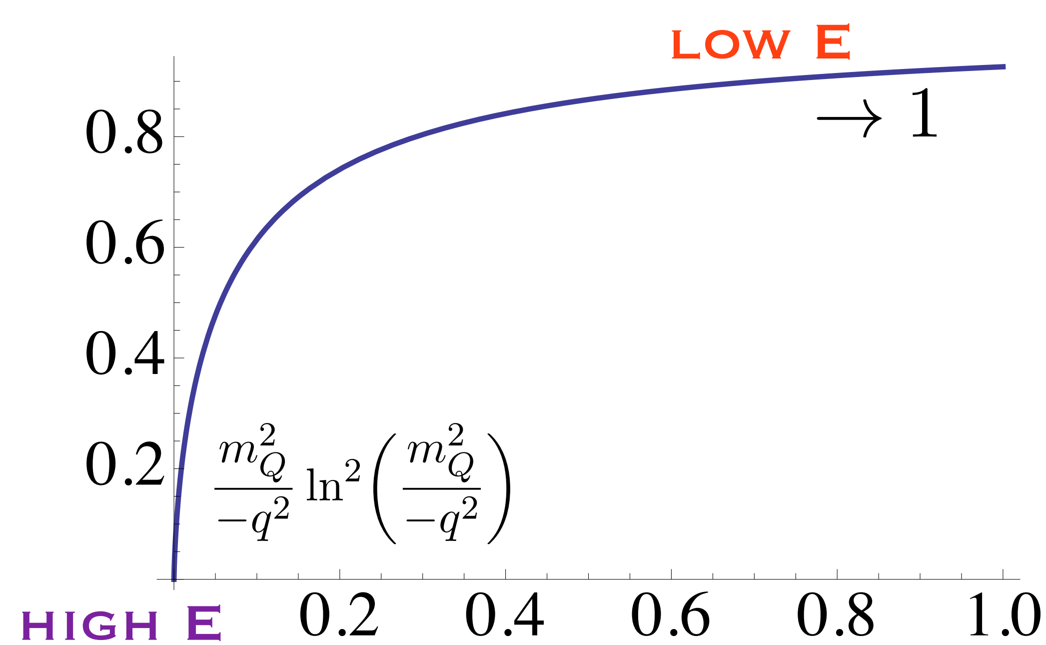
KJB, Choi, Im (2011)



$$\mathcal{A}_{1\mathrm{PI}}[a(k), g(p), g(p)] = \frac{g^2 C_{1\mathrm{PI}}}{32\pi^2 F_a}\delta^4(k+p+q)\epsilon_{\mu\nu\rho\sigma}k^\mu p^\nu \epsilon_1^\rho \epsilon_2^\sigma$$

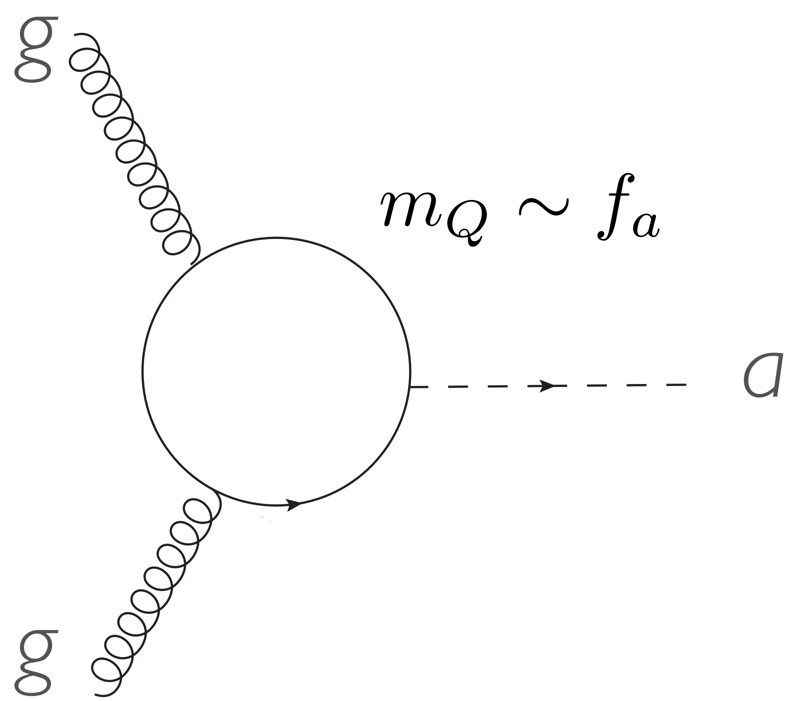
$$\boxed{\begin{aligned} C_{1\mathrm{PI}} &= x_Q + \mathcal{O}\left(\frac{m_Q^2}{E^2}\right) \quad \text{for} \quad E \ll m_Q \\ &= x_Q \frac{m_Q^2}{E^2}\ln^2\left(\frac{m_Q^2}{E^2}\right) \quad \text{for} \quad E \gg m_Q \end{aligned}}$$

suppressed at energy/temperature

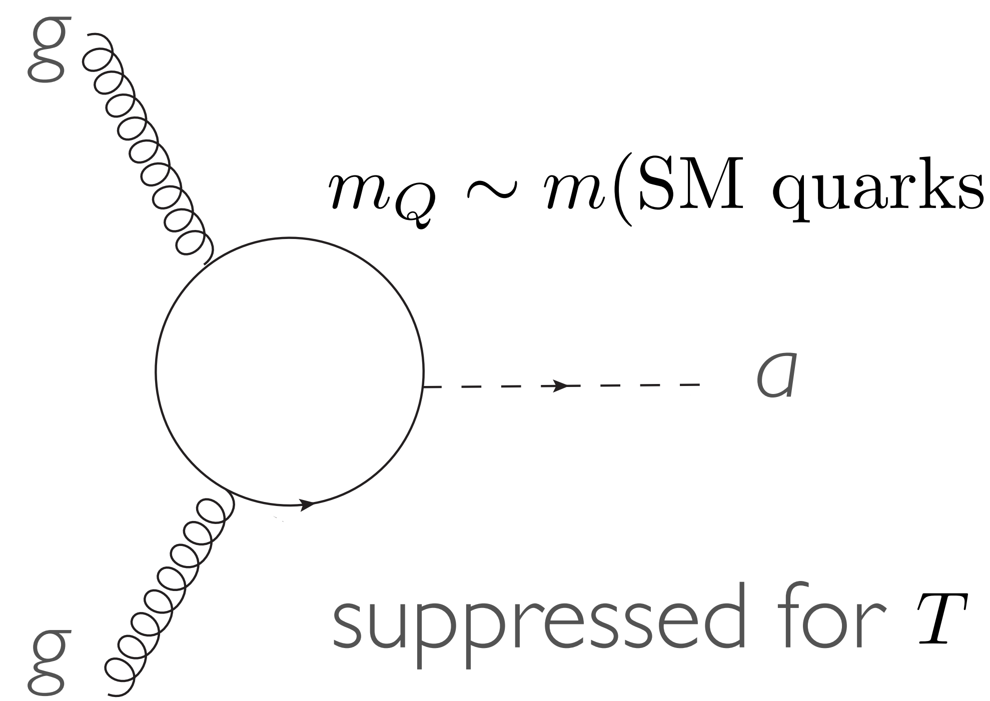


DFSZ MODEL

KSVZ



DFSZ



suppressed for $T > v_{\mathrm{EW}}$

DFSZ

$$\mathcal{L}_{\mathrm{DFSZ}} \supset B e^{ia/f_a} H_u H_d \sim \underline{i\frac{B}{f_a} a H_u H_d} + \cdots$$

feeble renormalizable coupling

DFSZ AXINO

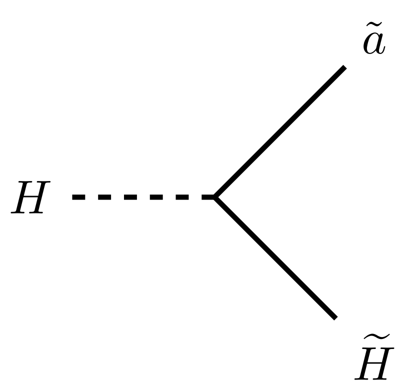
Supersymmetrizaion

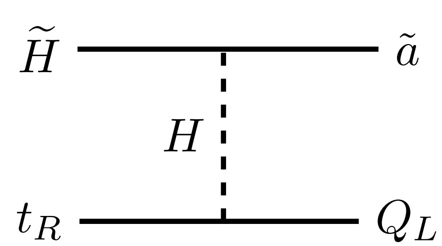
$$a \quad \longrightarrow \quad A = \frac{1}{\sqrt{2}}(s + ia) + \sqrt{2}\theta\tilde{a} + \theta^2 F_A$$

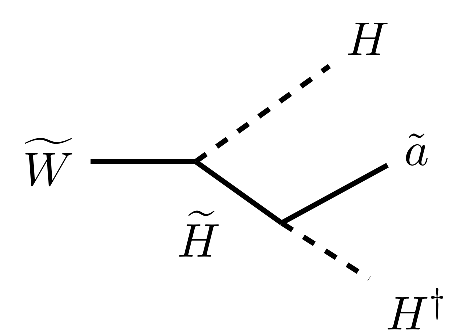
$$Be^{ia/f_a} H_u H_d \quad \Rightarrow \quad \int d^2\theta \mu e^{A/f_a} H_u H_d$$

+ ~~SUSY~~ couplings

Freeze-in production of Axino







$$\propto \left(\frac{\mu}{f_a}\right)^2$$

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LIGHT AXINO DM

mass: $m_{\tilde{a}} \sim \mathcal{O}(\mathrm{keV})$

- Axino (warm) DM could be possible
- Looking into detail of phase space distribution $f_{\tilde{a}}(t,p)$

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

collision term

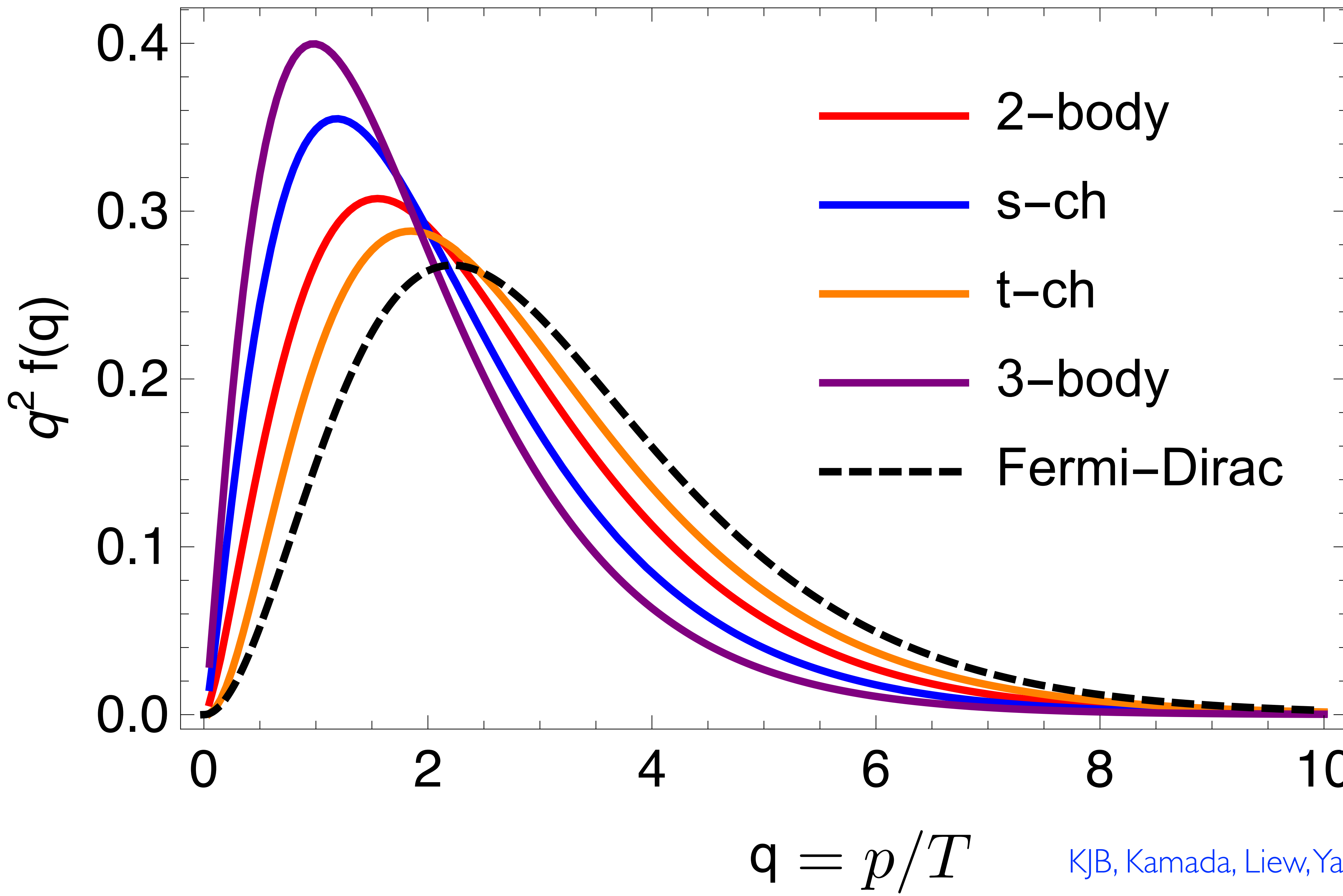
$$\longrightarrow \quad f_{\tilde{a}}(t_f,p) = \int_{t_i}^{t_f} dt \frac{1}{E_{\tilde{a}}} C\left(t, \frac{a(t_f)}{a(t)} p\right)$$

collision terms determine distribution

axino never be in equilibrium

follows "non-thermal" distribution when produced

DISTRIBUTION



KJB, Kamada, Liew, Yanagi (2017)

LYMAN-ALPHA FOREST

- Improving constraints on "warm dark matter mass"

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

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

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

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

- ***Warm Dark Matter***

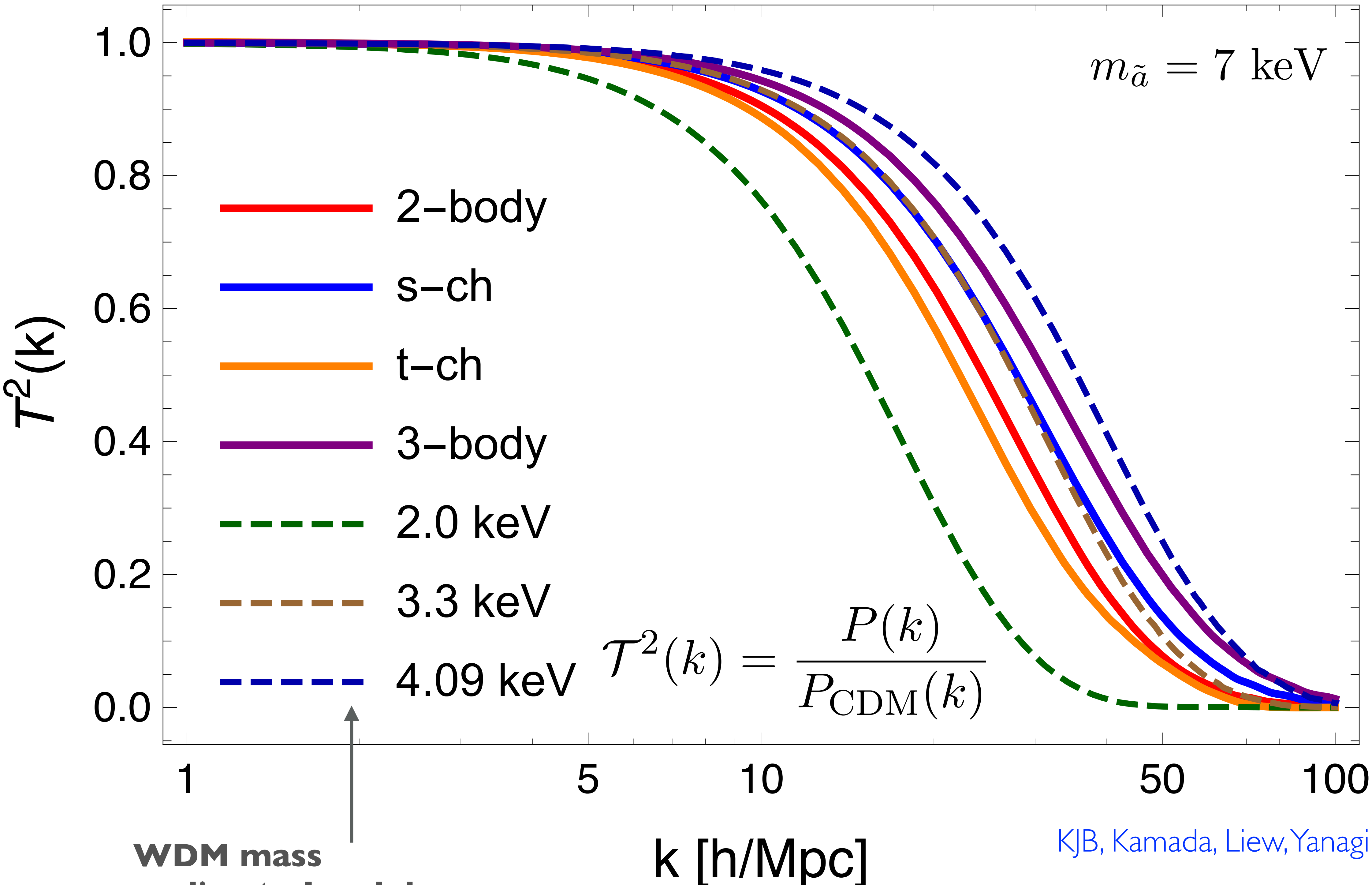
Ly-alpha constraints assume the Fermi-Dirac dist. and observed DM density

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

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

➡ need *linear matter power spectrum*

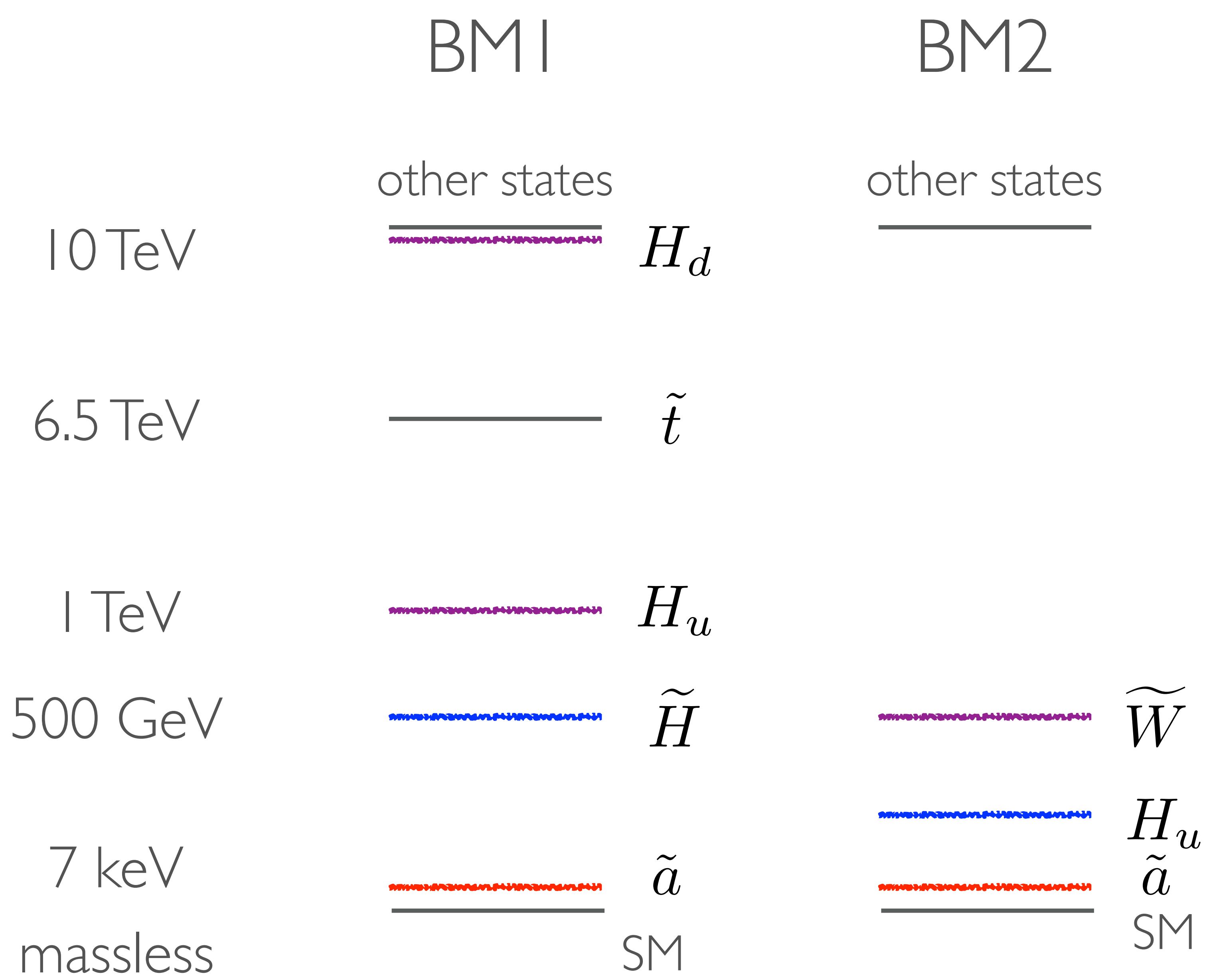
MATTER POWER SPECTRUM



KJB, Kamada, Liew, Yanagi (2017)

WDM mass corresponding to Ly-alpha

BENCHMARK SCENARIOS



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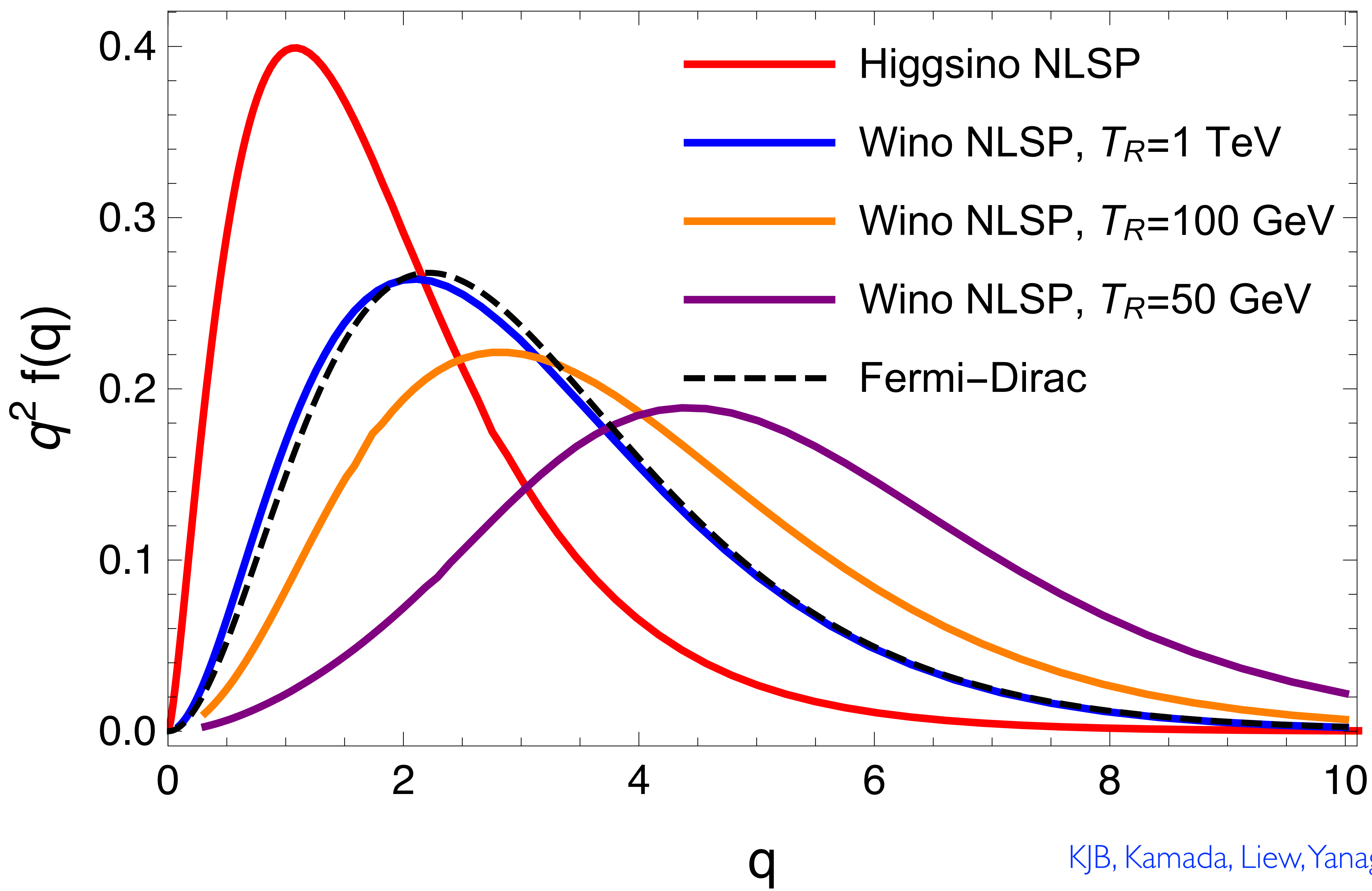
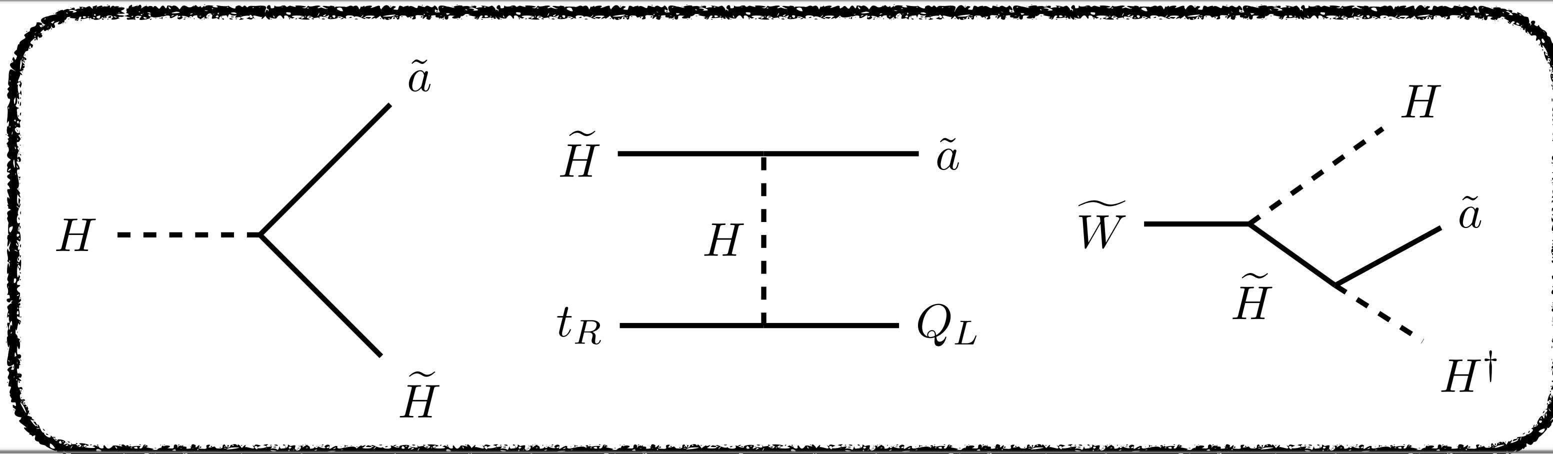
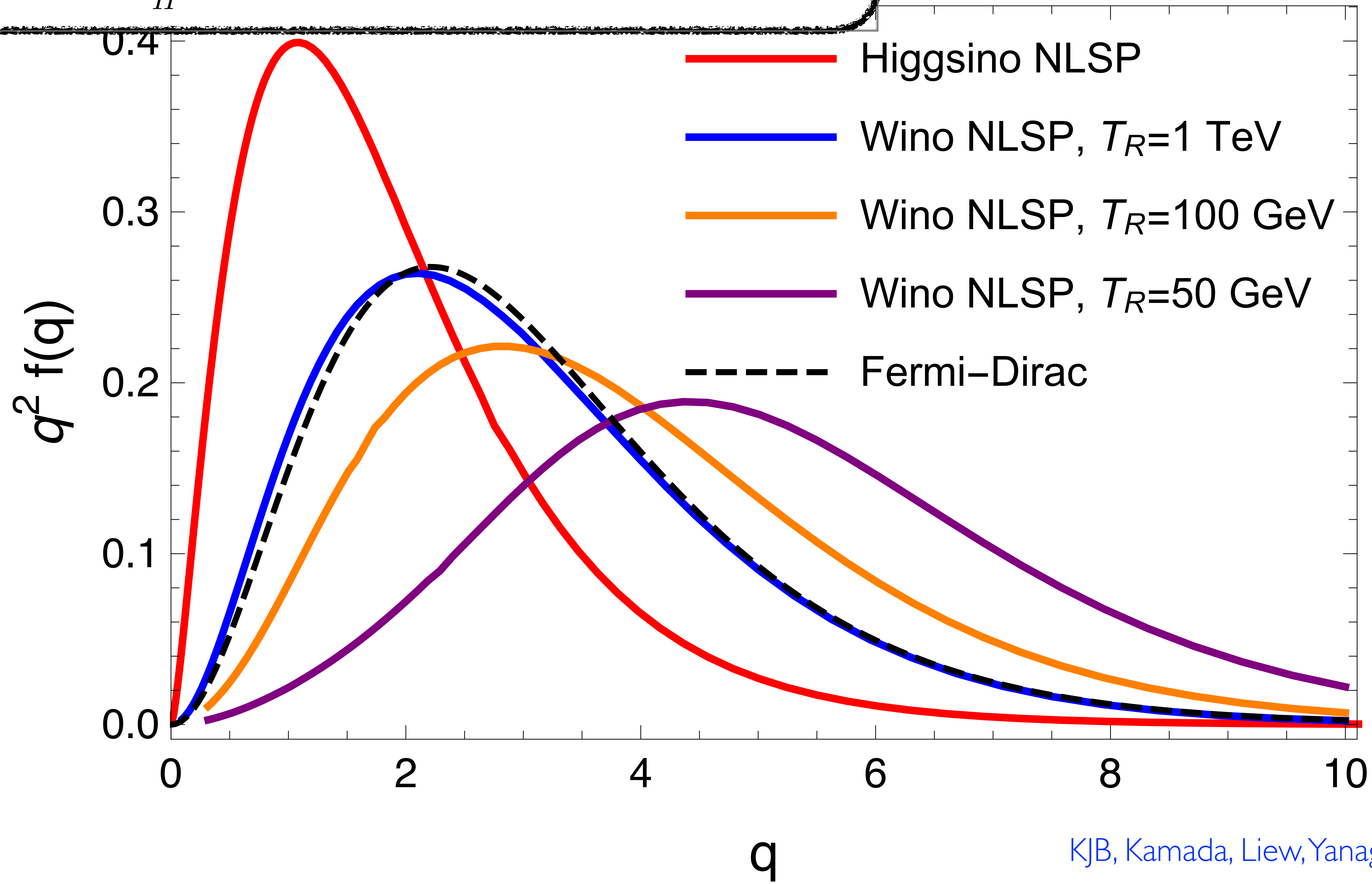


KJB, Kamada, Liew, Yanagi (2017)

ON





KJB, Kamada, Liew, Yanagi (2017)

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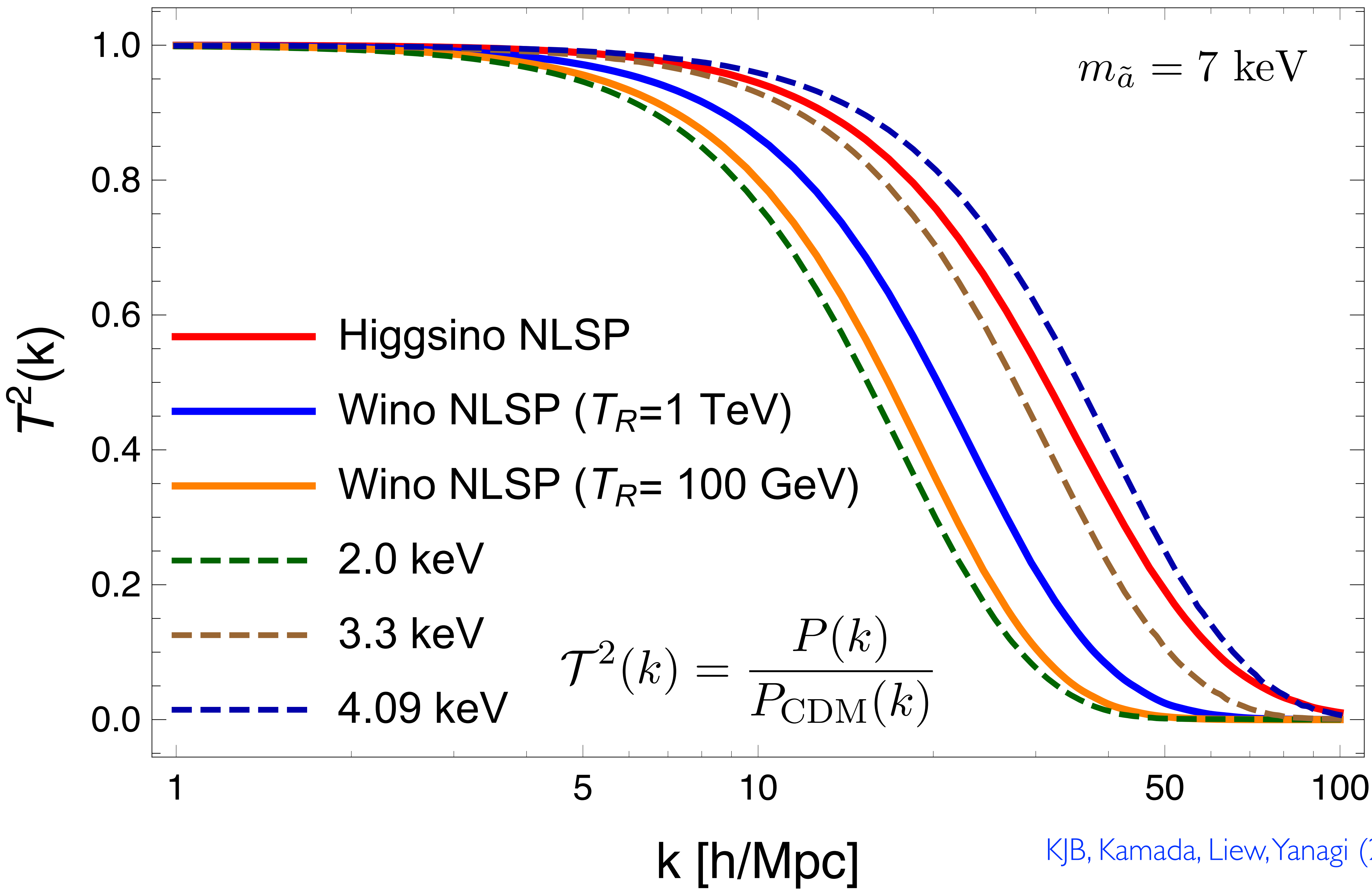
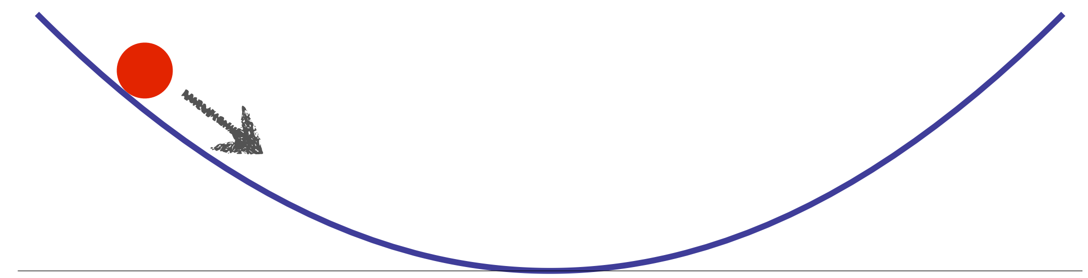


KJB, Kamada, Liew, Yanagi (2017)

SAXION DECAY

- Coherent oscillation of saxion:

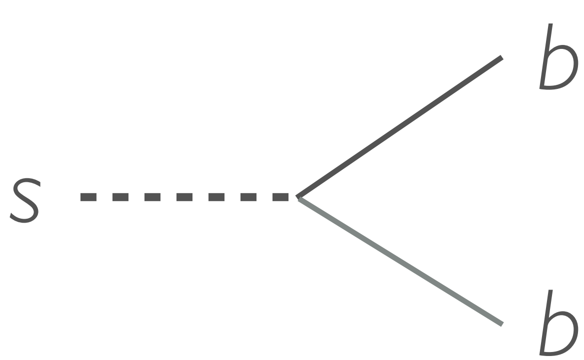
$$Y_s^{\rm CO} \simeq 1.9 \times 10^{-6} \left(\frac{\rm GeV}{m_s}\right) \left(\frac{\min[T_R, T_s]}{10^7\,{\rm GeV}}\right) \left(\frac{s_0}{10^{12}\,{\rm GeV}}\right)^2$$



- 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



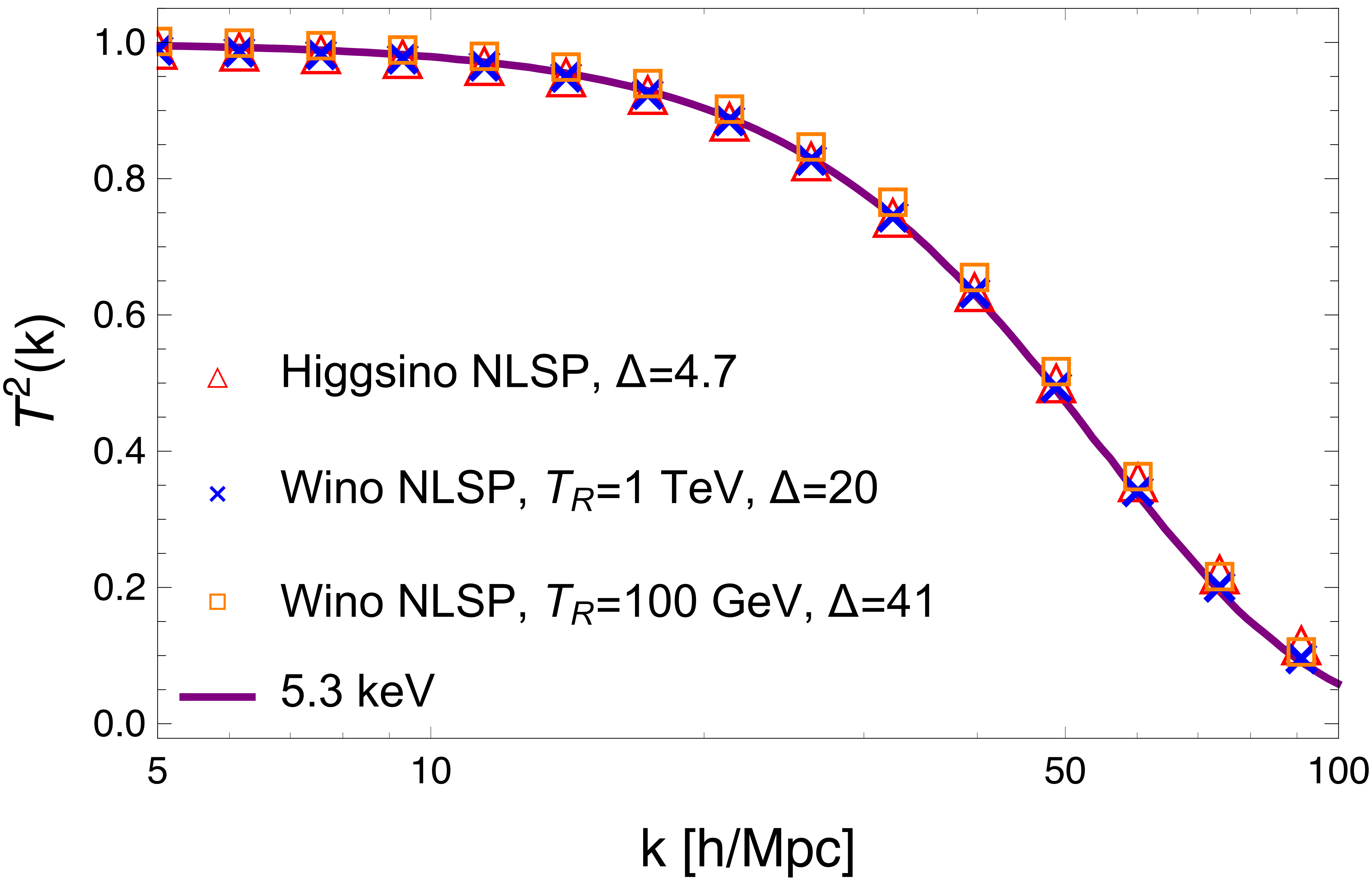
$$v_{\rm PQ} = 2.5 \times 10^{10}\ {\rm GeV}$$

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

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

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

ENTROPY



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

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

- An alternative to WIMP: Freeze-In Dark Matter
- Axino in DFSZ model is a freeze-in DM candidate.
  - a-G-G is suppressed at high T; feeble tree-level coupling
  - colder dist. than thermal case; Lyman-alpha forest constraints
- Future probe of freeze-in scenario:
  - other small(er) scale observations? Donghui's talk
  - collider searches for NLSP decay e.g. MATHUSLA
- More general models of Freeze-in DM
  - multi-components; late decays; ...