Light feebly interacting massive particle: freeze-in production and galactic-scale structure formation

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Based on
Kyu Jung Bae, AK, Seng Pei Liew, and Keisuke Yanagi, PRD, 2018 and JCAP, 2018
Kyu Jung Bae, Ryusuke Jinno, AK, and Keisuke Yanagi, in preparation

Jun. 12, 2019 @ Kavli IPMU

Dark matter

Accumulated evidences from observations of the Universe

Known properties

- long-lived over the age of the Universe
- accounting for about 30% of the present energy density of the Universe $\Omega_{\rm dm}h^2 \simeq 5\Omega_{\rm baryon}h^2 \simeq 0.12$
- feebly-interacting with photon and baryon
- not too hot to smear out primordial density contrast

No standard model (SM) particle satisfies the properties

→ long-standing mystery in cosmology and particle physics

WIMP Miracle

Weakly interacting massive particle: WIMP

Stability: new $\mathbb{Z}_2$ symmetry e.g., matter parity: $U(1)_{B-L} \to (-1)^{3(B-L)}$

Abundance: annihilation $\chi\chi \to AA$ χ : WIMP A : SM

- thermal freeze-out: TeV-scale (!) interaction
- indirect detection (cosmic ray) experiments

Interaction with SM particles: (sub-) weak scale

- direct detection (nuclei recoil) experiments

Non-relativistic: cold dark matter

Related with TeV-scale new physics (!) that explains the origin of the weak scale (naturalness problem)

- collider experiments

Pragmatic WIMP

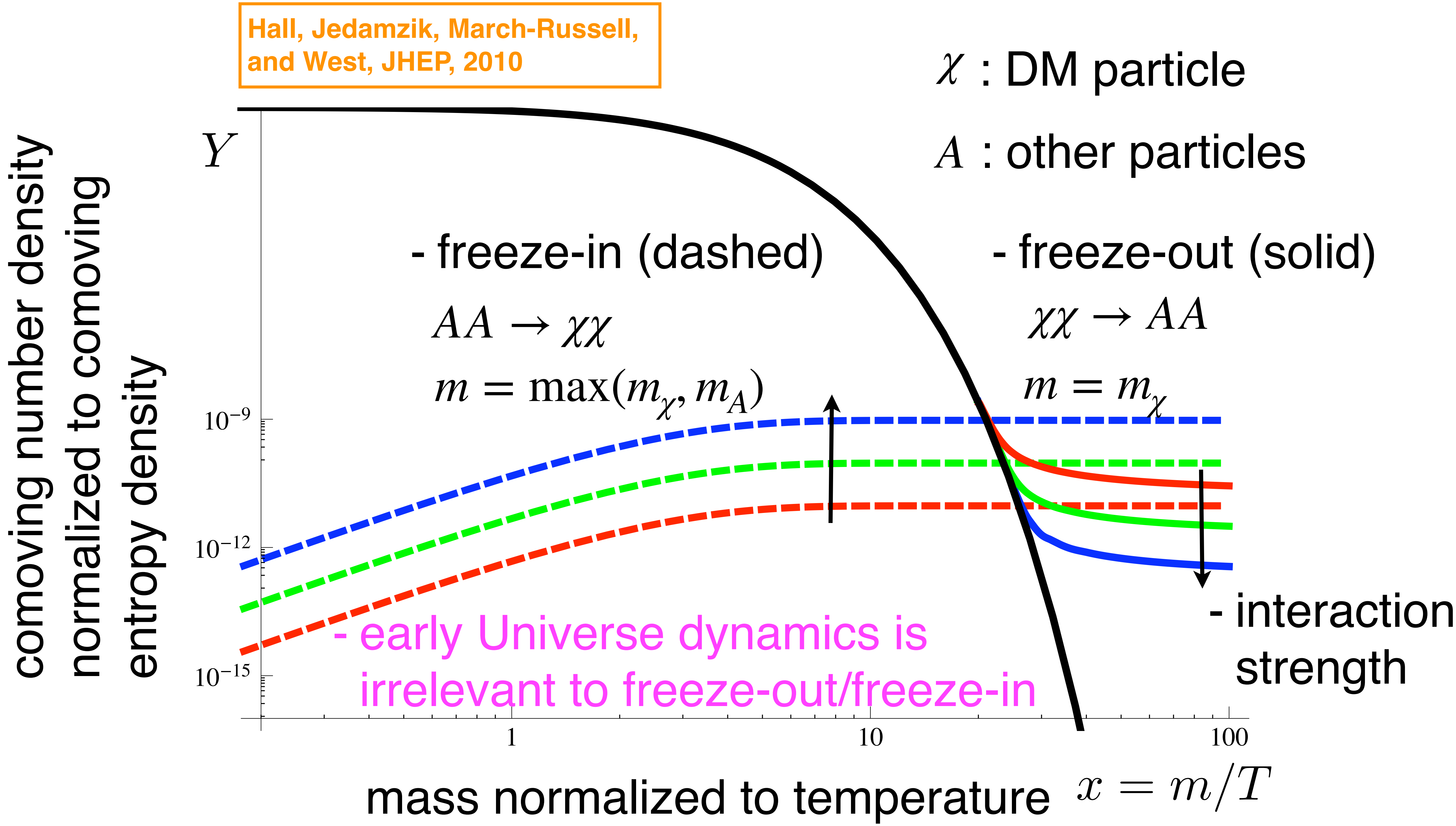
LHC null-detection of TeV-scale new physics

- something wrong in naturalness and postulated solutions
- no convincing reason for new physics at the TeV scale
    - grand unified theory (GUT)?
        → mini-split supersymmetry (SUSY)

Still WIMP is a good benchmark (even though not a miracle)

- direct/indirect detection experiments
- thermal freeze-out: relic abundance is insensitive to unconstrained ultraviolet physics (early Universe dynamics)

Thermal production



Freeze out: WIMP

Freeze in: Feebly Interacting Massive Particle (FIMP)

Light FIMP

Light (keV-scale) FIMP

Stability: light + feeble interaction (quasi-stable)

Abundance: freeze-in via out-of-equilibrium processes

- renormalizable interaction with tiny coefficient

Interaction with SM particles: super weak

- indirect detection (X-ray) experiments $\chi \to \gamma \cdots$

e.g., 3.5 keV line → 7 keV FIMP

Bulbul, Markevitch, Foster, Smith, Loewenstein, and Randall, ApJ, 2014

Boyarsky, Ruchayskiy, Iakubovskyi, and Franse, PRL, 2014

Non-relativistic: warm dark matter

- alter galactic-scale structure of the Universe

Collider: long-lived particle A

if $A \to \chi B$ is dominant B : SM

Example: light axino

Axion: Nambu-Goldstone (NG) boson of PQ symmetry

- dynamically explaining why CP is a good symmetry in strong interaction

Axino: fermionic SUSY partner of axion $A = \frac{s+ia}{\sqrt{2}} + \sqrt{2}\theta\tilde{a} + \theta^2 \mathcal{F}_A$

c.f., bosonic SUSY partner: saxion

Goto and Yamaguchi, PLB, 1992

Chun, Kim, and Nilles, PLB, 1992

Chun and Lucus. PLB, 1995

Axino mass: naively ~ gravitino mass, but light (keV-scale) axino is also possible

DFSZ axion model: PQ-charge assignment of SM fields

Kim, PRL, 1979

Shifman, Vainshtein, and Zakharov, NPB, 1980

- explaining why μ term is at the TeV scale

Kim and Nilles, PLB, 1984

- long lifetime of proton w/o R parity

Dine, Fischer, and Srednicki, PLB, 1981

Zhitnitsky, Sov. J. Nucl. Phys. B, 1980

c.f., KSVZ: heavy vector-like quark

Light axino interaction

Chun, PLB, 1999 | Choi, Chun, Hwang, PRD, 2001 | Chun and Kim, JHEP, 2006

Bae, AK, Liew, and Yanagi, PRD, 2017

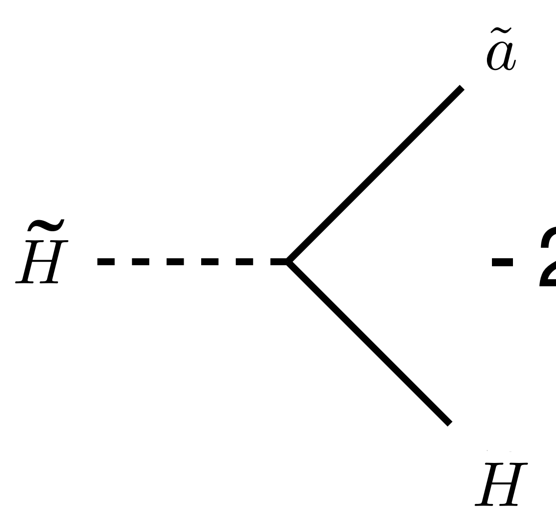
R parity violating interaction → axino-neutrino mixing

$$\theta \simeq 10^{-5}\left(\frac{\epsilon}{10^{-5}}\right)\left(\frac{\mu}{400\,\mathrm{GeV}}\right)\left(\frac{7\,\mathrm{keV}}{m_{\tilde{a}}}\right)\left(\frac{10^{10}\,\mathrm{GeV}}{v_{\mathrm{PQ}}}\right)$$

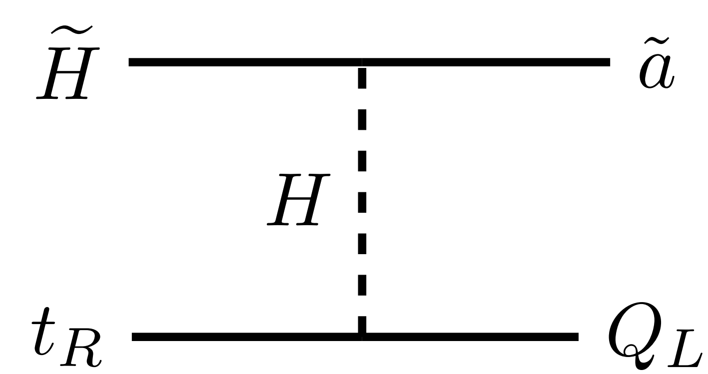
- axino as sterile neutrino

R parity preserving interaction → freeze-in production of axino

$$W_{\mathrm{int}} = \frac{2\mu}{v_{\mathrm{PQ}}} A H_u H_d$$



- 2-body decay



- scattering
(+ s-channel)

We will discuss

Galactic-scale structure of the Universe

part 1

- small-scale challenges of cold dark matter
- $m_{\rm WDM}$ as a benchmark

Constraining FIMPs from structure formation

part 2

- mapping from $m_{\rm WDM}$
- analytic formulas in simplified models

- suppose the FIMP mass is inferred by X-ray!

More generic approach

part 3

- (α, β, γ) parametrization
- machine learning

Part 1: Galactic-scale structure

Possible discrepancies from the CDM (WIMPs) prediction on galactic (sub-Mpc) scales (small-scale issues)

Bullock and Boylan-Kolchin, ARAA, 2018

- missing satellite problem: observed number of dwarf spheroidal galaxies is $\mathcal{O}(10)$ times smaller than in simulations

Klypin, Kravtsov, Valenzuela, and Prada, ApJ, 1999

Moore, Ghigna, Governato, Lake, Quinn, Stadel, and Tozzi, ApJ, 1999

- too-big-to-fail problem: ~10 missing galaxies are the biggest subhalos in simulations (to big to fail to be detected)

Boylan-Kolchin, Bullock, and Kaplinghat, MNRAS, 2011 and 2012

The issues may be attributed to incomplete understanding of complex astrophysical processes (subgrid physics)

APSOTLE collaboration, MNRAS, 2016

NIHAO collaboration, MNRAS, 2016

FIRE cllaboration, ApJ, 2016

The issues are easily explained by alternatives to CDM

- WDM (FIMPs) $m_{\rm WDM} = \mathcal{O}(1)\,\mathrm{keV}$

- beyond WIMP?

Fiducial model of WDM

Thermal WDM: early decoupled fermion like SM neutrino

- FIMPs are in thermal equilibrium in the early Universe through non-renormalizable interaction (not freeze-in) and decouple when relativistic   e.g., light gravitino

Fermi-Dirac distribution w/ 2 spin degrees of freedom:

$$f_{\rm WDM} = \frac{1}{e^{p/T_{\rm WDM}} + 1}$$

Two parameters: temperature $T_{\rm WDM}$ and mass $m_{\rm WDM}$

$T_{\rm WDM}$ is determined by the (observed) DM mass density for a given $m_{\rm WDM}$:

$$\Omega_{\rm WDM} h^2 = \left(\frac{m_{\rm WDM}}{94\,{\rm eV}}\right) \left(\frac{T_{\rm WDM}}{T_\nu}\right)^3$$

Linear matter power spectrum

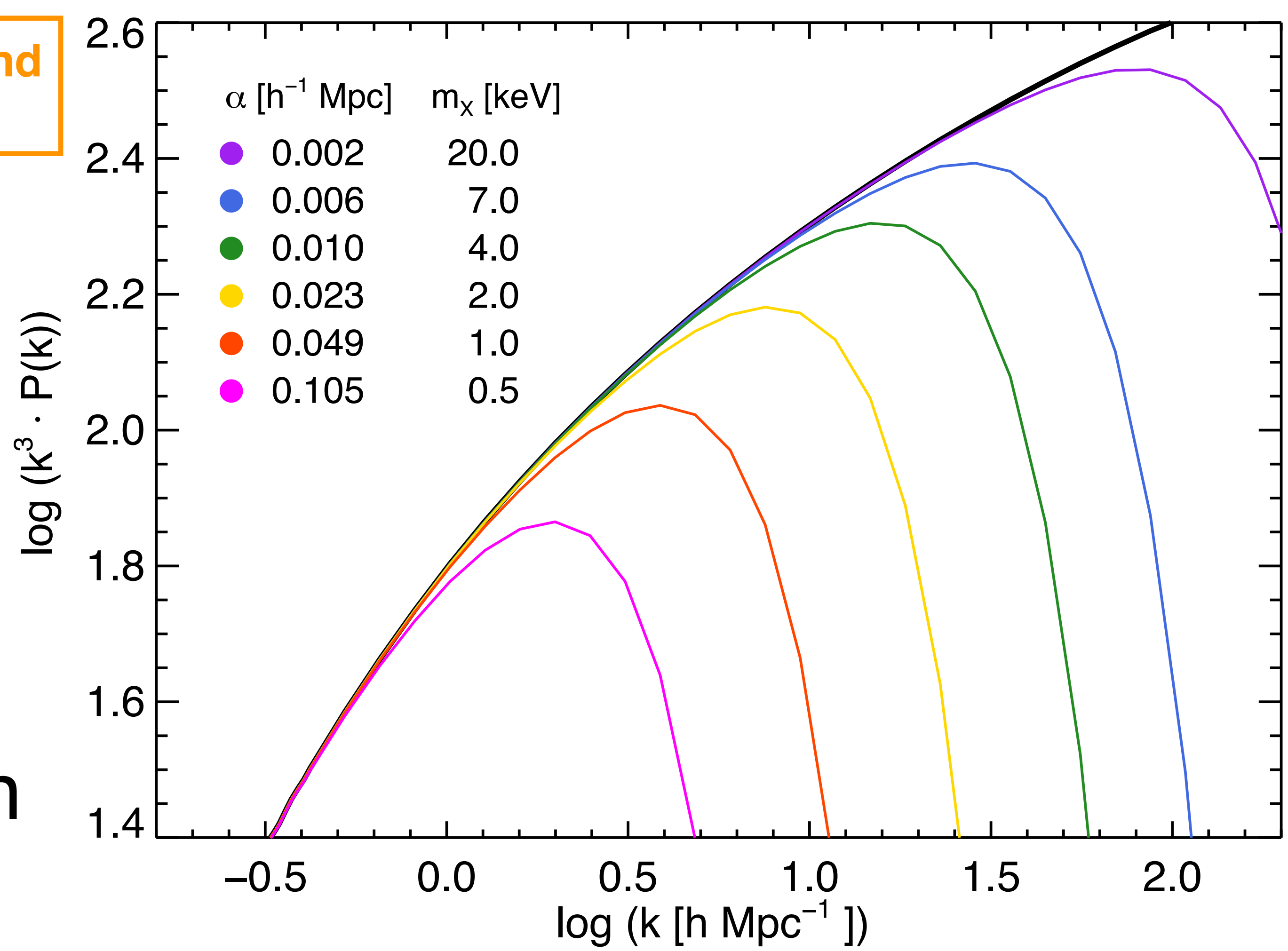
$m_{\rm WDM}$ parametrizes the linear matter power spectrum:

Viel, Lesgourgues, Haehnelt, Matarrese, and Riotto, PRD, 2005

$$P_{\rm WDM}/P_{\rm CDM} = T^2_{\rm WDM}(k) = \left[1 + (\alpha k)^{2\nu}\right]^{-10/\nu} \qquad \nu = 1.12$$

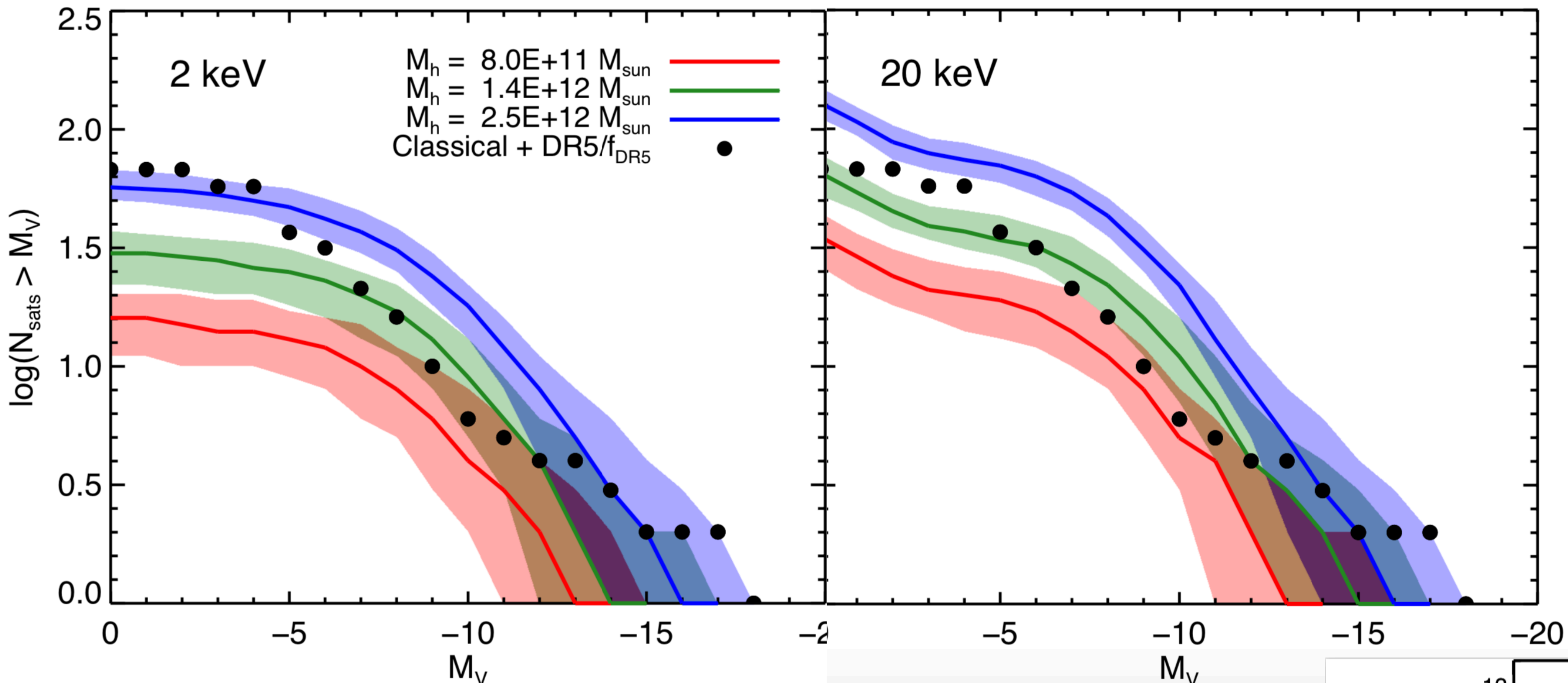
$$\alpha = 0.049\,{\rm Mpc}/h \left(\frac{m_{\rm WDM}}{\rm keV}\right)^{-1.11} \left(\frac{\Omega_{\rm WDM}}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22}$$

Kennedy, Frenk, Cole, and Benson, MNRAS, 2014



WDM provides less seed for small-scale structure formation

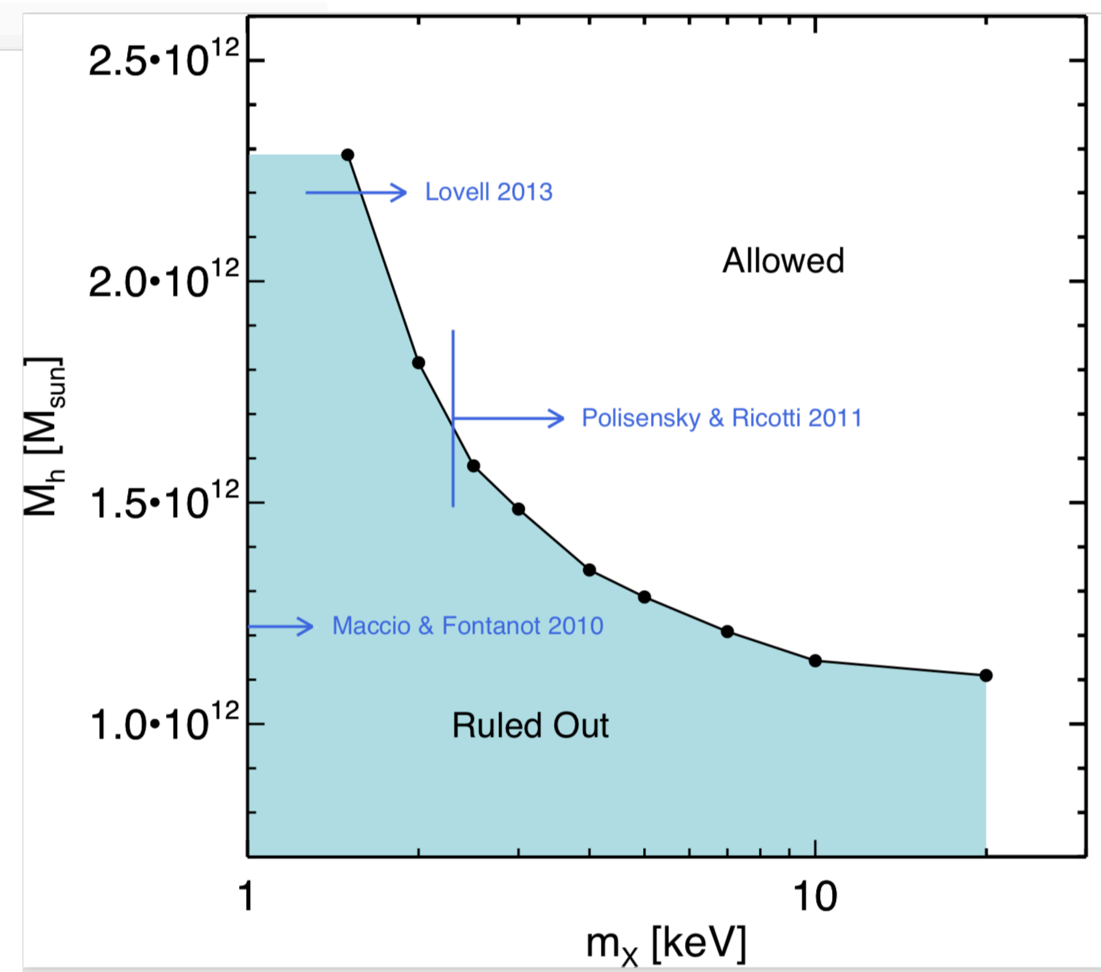
Missing satellite problem w/ WDM



Kennedy, Frenk, Cole, and Benson, MNRAS, 2014

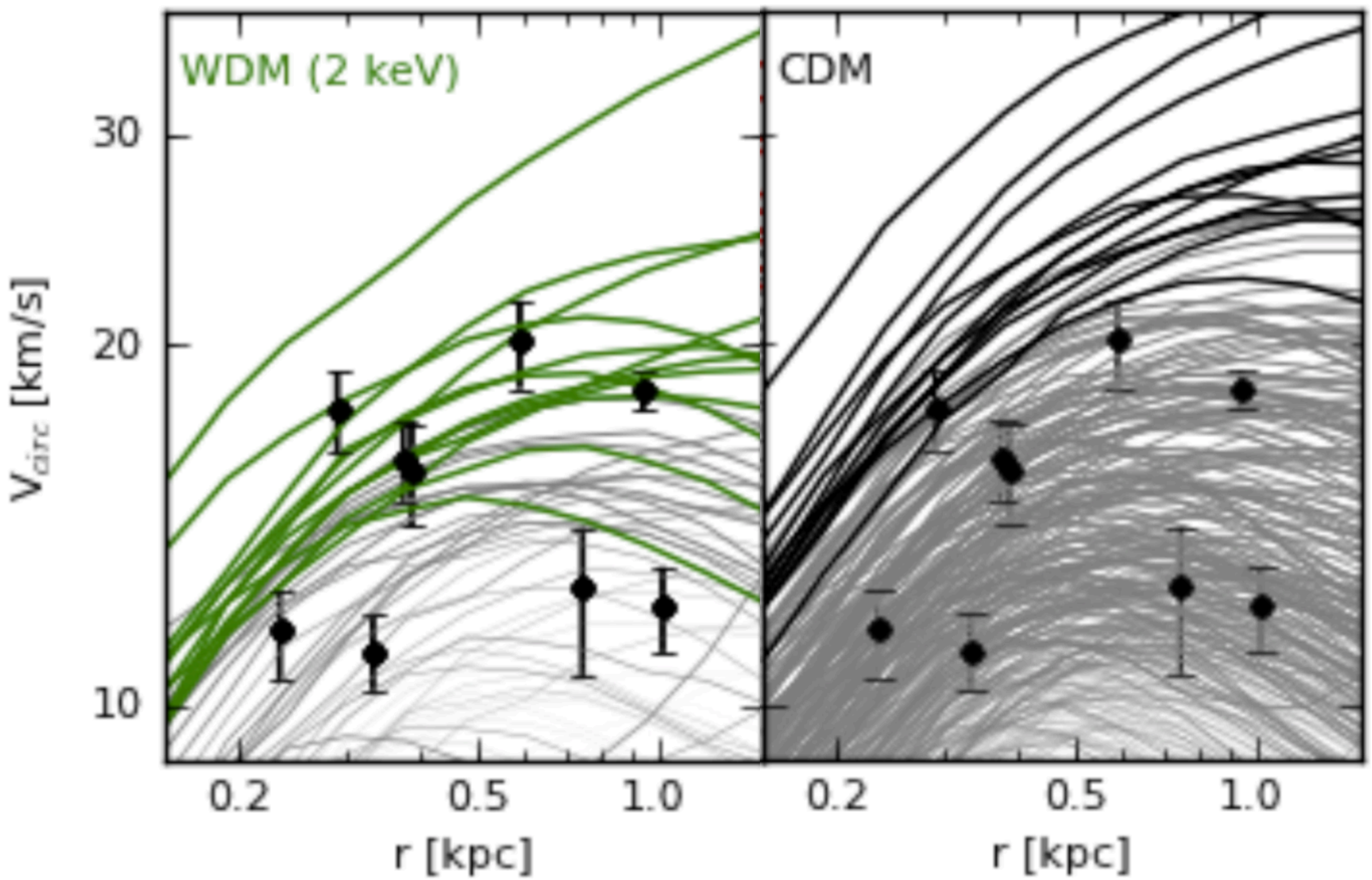
WDM reduces a predicted number of satellite galaxies

Should not go below the observed number
→ $m_{\mathrm{WDM}} \gtrsim 2\,\mathrm{keV}$



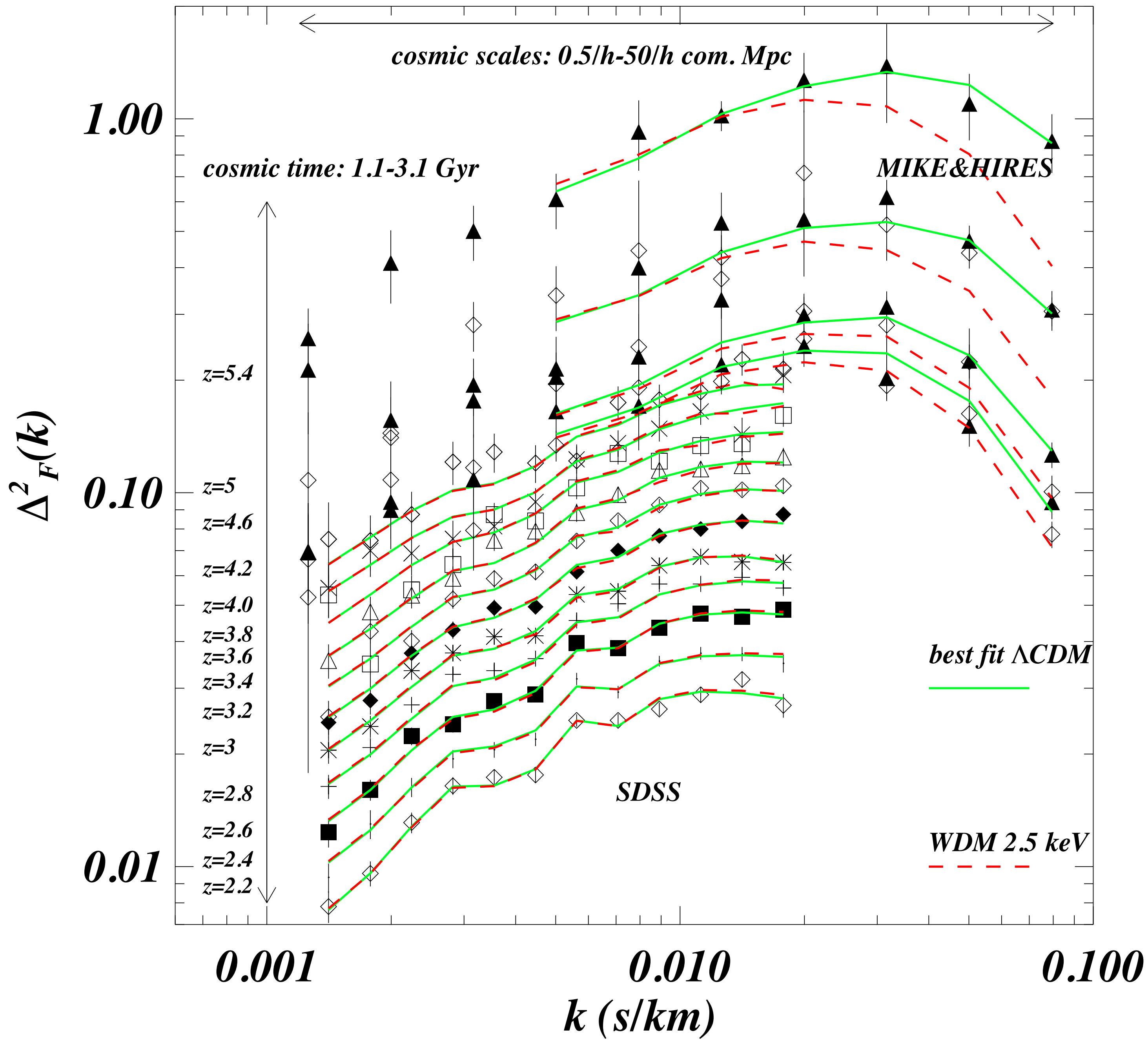
Too-big-to-fail problem w/ WDM

Schneider, Anderhalden, Maccio, and Diemand, MNRAS, 2014



WDM also reduces a predicted number of bigger subhalos than observed satellites

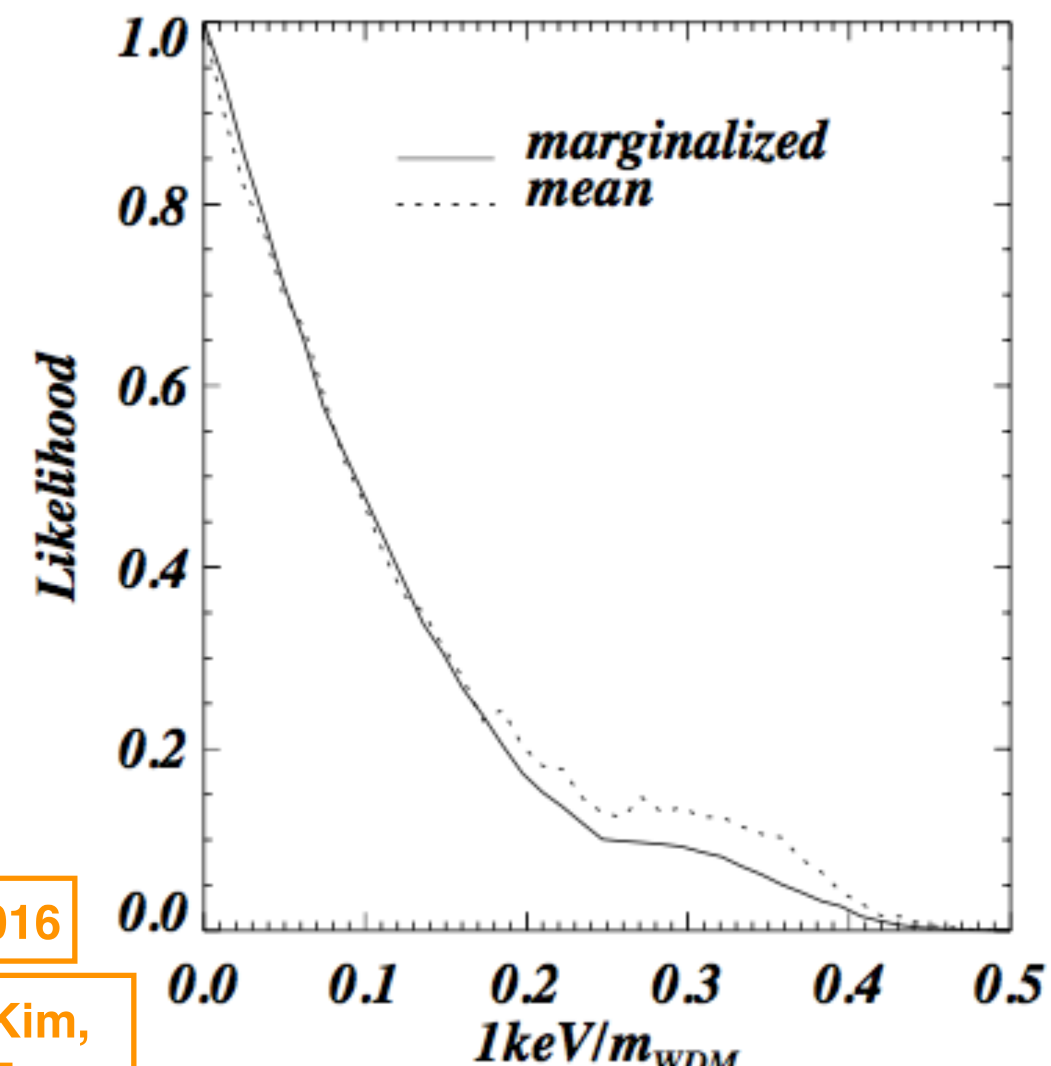
Lyman-α forest constraints on WDM



Viel, Becker, Bolton, and Haehnelt, PRD, 2013

WDM suppresses clumping of neutral hydrogen probed by Lyman-α forest in high-z quasar spectra

→ $m_{\rm WDM} \gtrsim 3.3\,{\rm keV}$



c.f., $m_{\rm WDM} \gtrsim 2.0, 4.09, 5.3\,{\rm keV}$

Viel, Lesgourgues, Haehnelt, Matarrese, and Riotto, PRD, 2005

Baur, Palanque-Delabrouille, Yèche, Magneville, and Viel, JCAP, 2016

Iršič, Viel, Haehnelt, Bolton, Cristiani, Becker, D'Odorico, Cupani, Kim, Berg, López, Ellison, Christensen, Denny, and Worseck, PRD, 2017

Part 2: FIMP ≠ thermal WDM

One cannot conclude that 7 keV FIMP DM (for 3.5 keV line) is cold enough from $m_{\rm WDM} \gtrsim 3.3\,{\rm keV}$

Thermal WDM: entropy conservation after decoupling

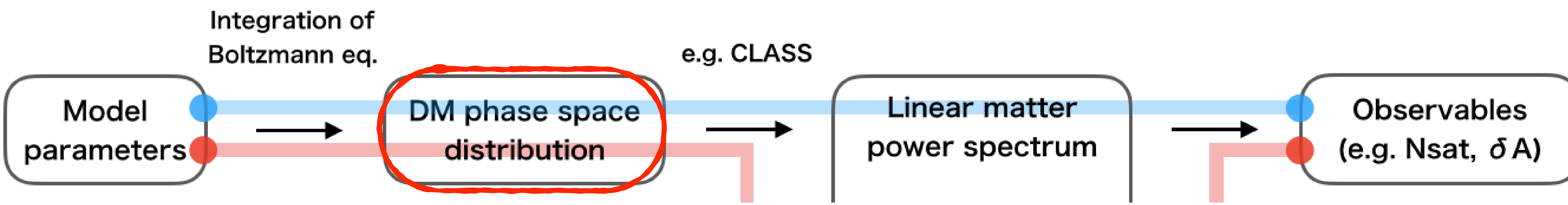
$$T_{\rm DM} = \left(\frac{g_*(T)}{g_*(T_{\rm dec})}\right)^{1/3} T$$

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

- extra entropy production (~100) after decoupling is needed to realize keV-scale WDM

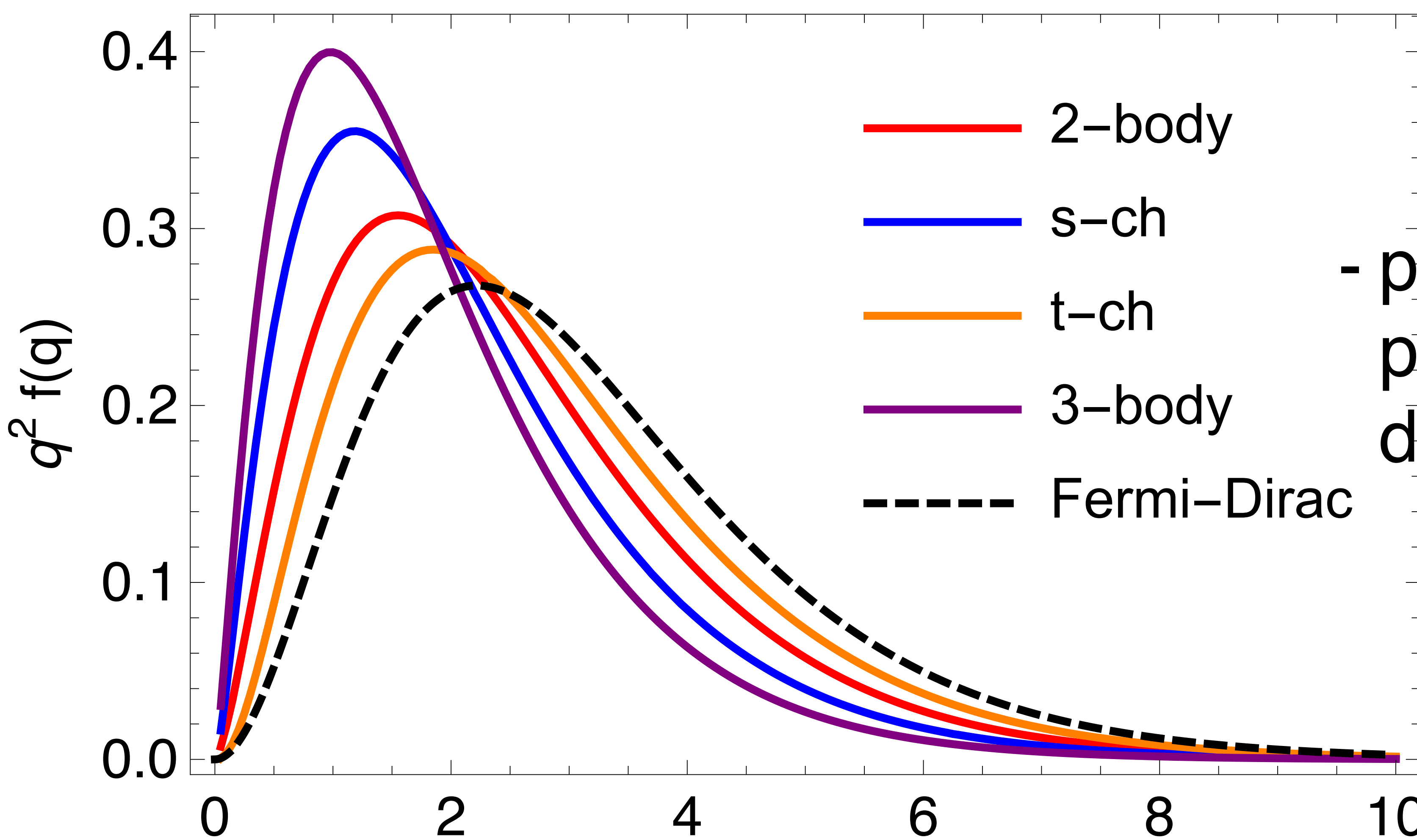
Thermal WDM is much colder than naively expected
→ lower bound on the FIMP mass w/o entropy production is higher

Constraining FIMP



DM phase space distribution

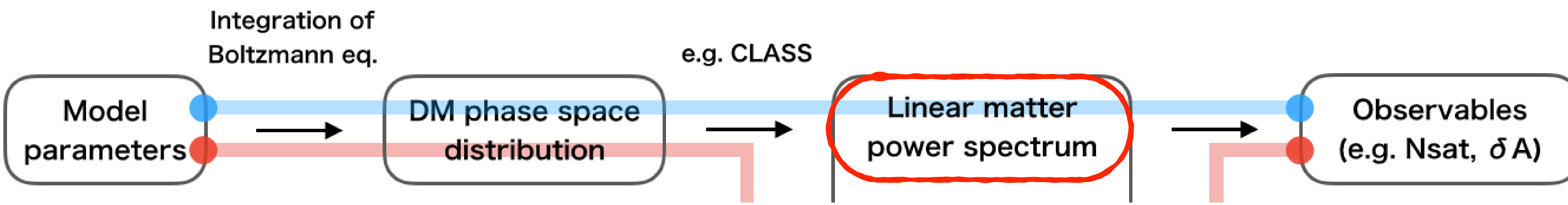
Bae, AK, Liew, and Yanagi, JCAP, 2017



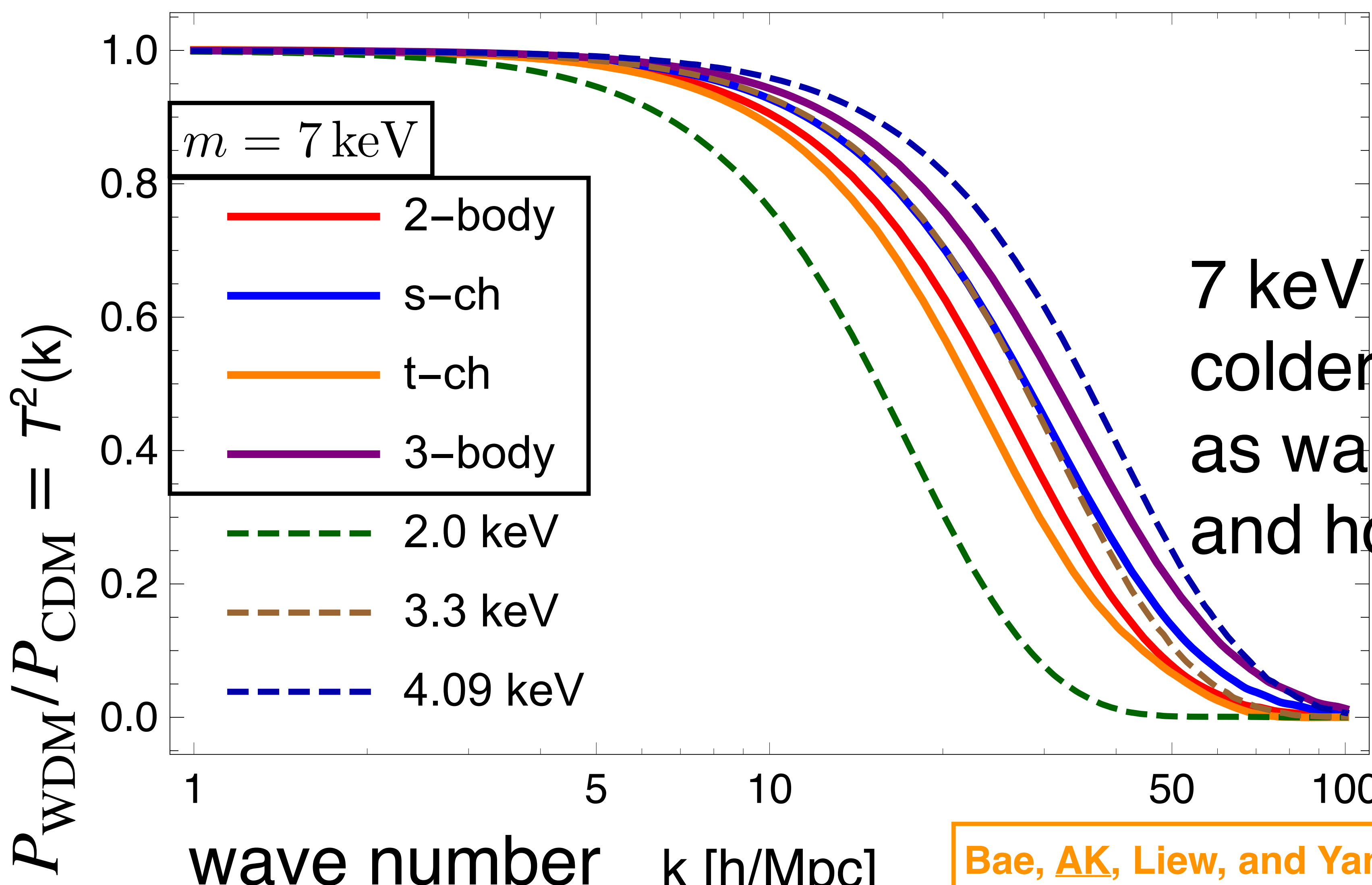
- production process dependent

normalized comoving momentum q $= p/T_{\rm WDM}$ $\quad T_{\rm DM} = \left(\frac{g_*(T)}{g_*(T_{\rm dec})}\right)^{1/3} T$

7 keV FIMP vs thermal WDM



Linear matter power spectrum $g_*(T_{\rm dec}) = 106.75$



7 keV FIMP DM is
colder than $m_{\rm WDM} = 2.0\,\mathrm{keV}$,
as warm as $m_{\rm WDM} = 3.3\,\mathrm{keV}$,
and hotter than $m_{\rm WDM} = 4.09\,\mathrm{keV}$

Bae, AK, Liew, and Yanagi, JCAP, 2017

Warmness

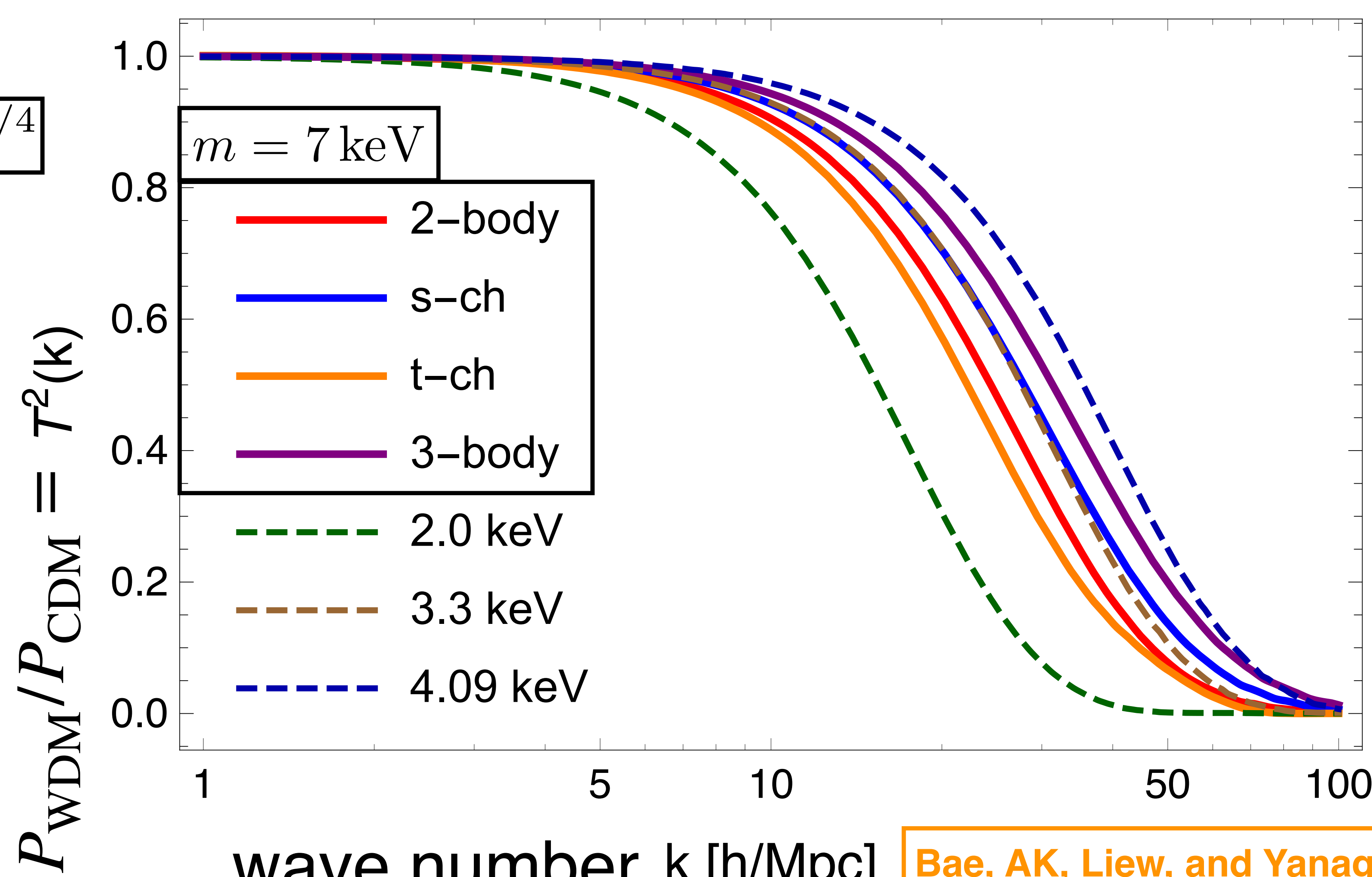
Quantity characterize warmness of DM:

$$\sigma^2 = \frac{T_{\rm DM}^2}{m^2}\tilde{\sigma}^2, \quad \tilde{\sigma}^2 = \frac{\int dq q^4 f(q)}{\int dq q^2 f(q)} \rightarrow m = 7\,\mathrm{keV}\left(\frac{m_{\rm WDM}}{2.5\,\mathrm{keV}(\tilde{\sigma}/3.6)^{-3/4}}\right)^{4/3}$$

$$g_*(T_{\rm dec}) = 106.75$$

AK, Yoshida, Kohri, and Takahashi, JCAP, 2013

$2.5\,\mathrm{keV}(\tilde{\sigma}/3.6)^{-3/4}$
$= 2.9\,\mathrm{keV}$
$= 3.2\,\mathrm{keV}$
$= 2.7\,\mathrm{keV}$
$= 3.6\,\mathrm{keV}$

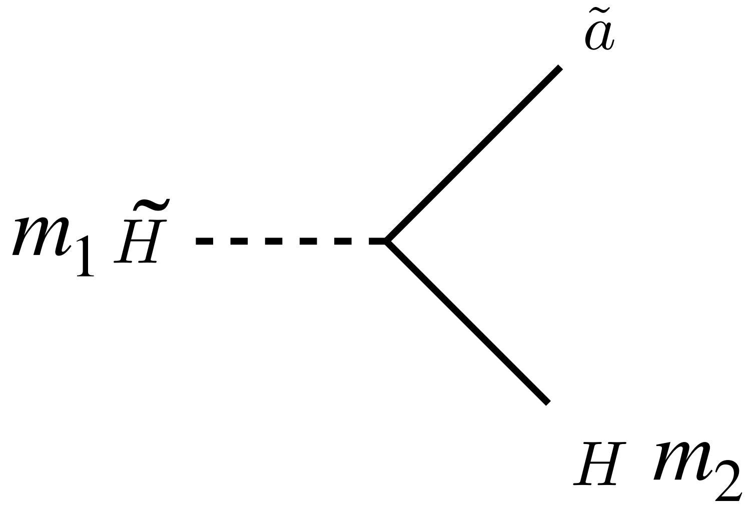


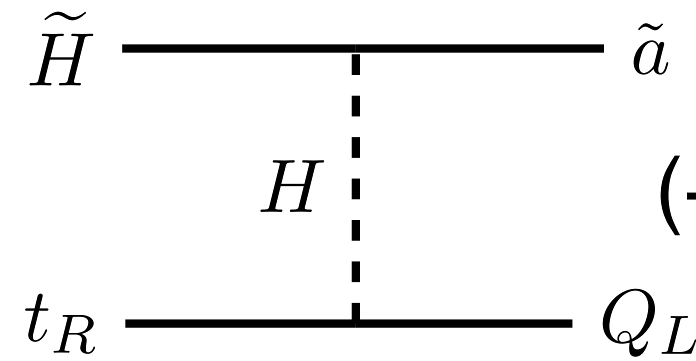
Bae, AK, Liew, and Yanagi, JCAP, 2017

Analytic mapping via warmness

Analytic formulas of $f(q)$ are available in a simplified model

AK and Yanagi, in preparation



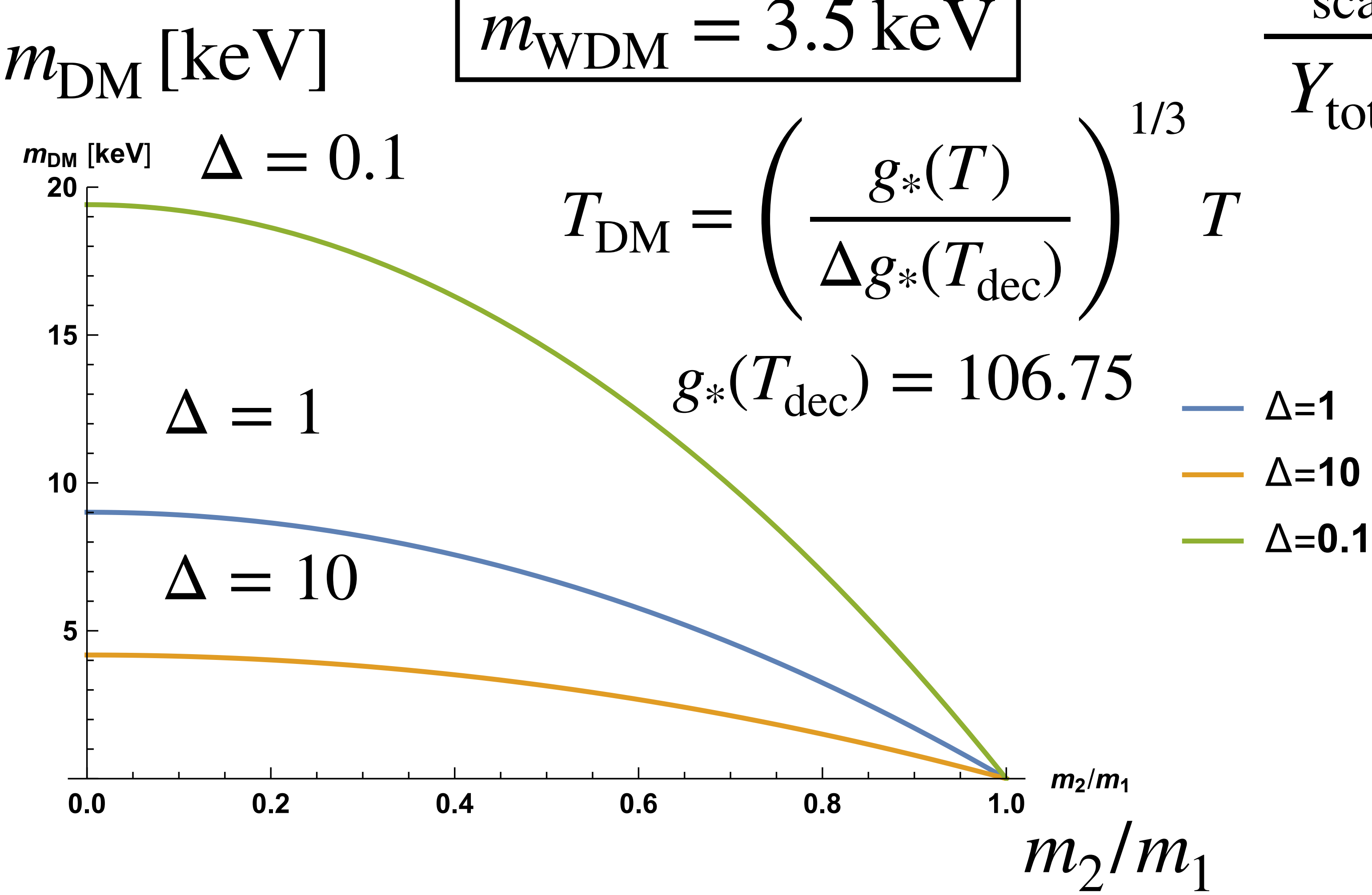


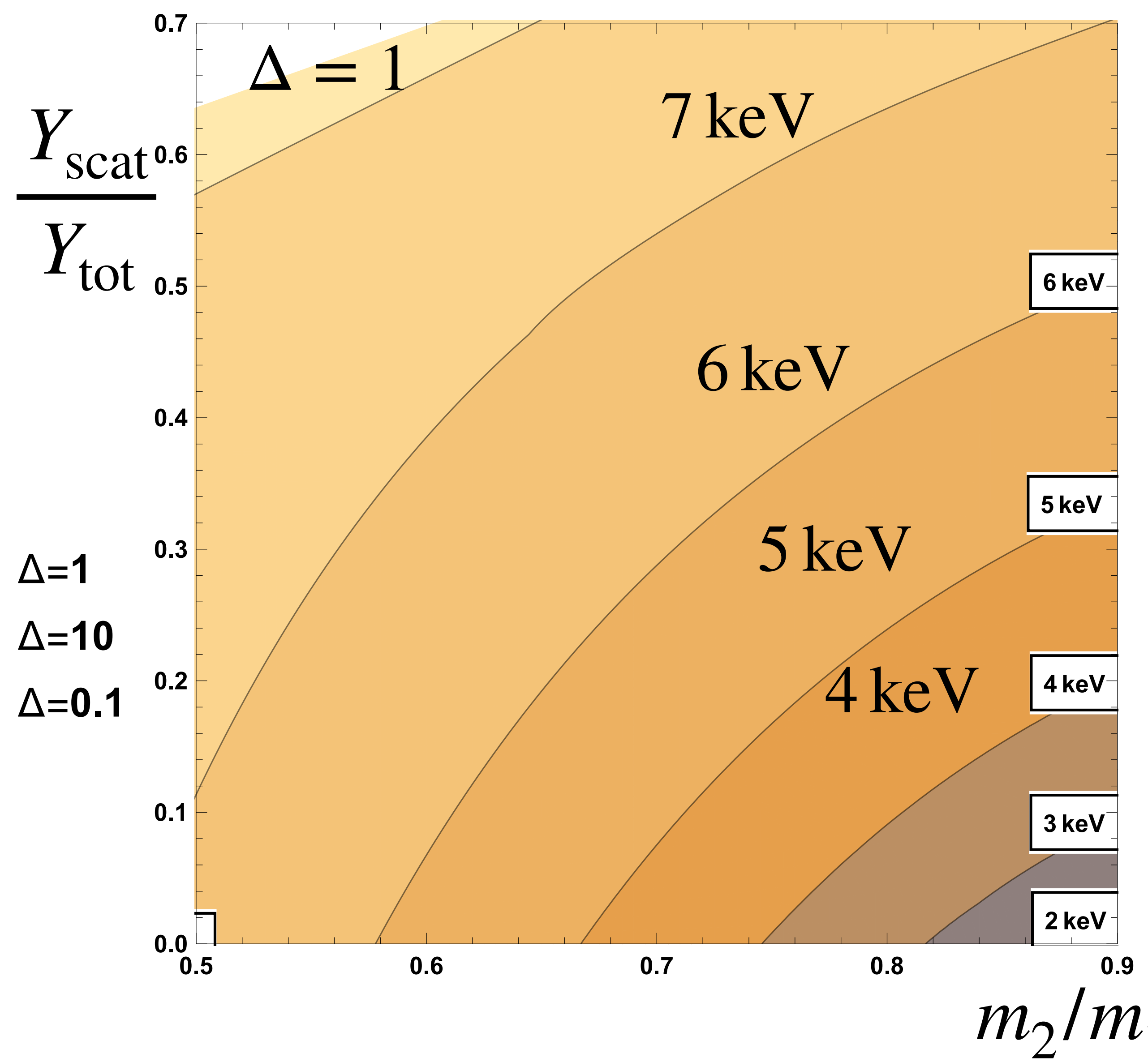
(+ s-channel)

$$\boxed{m_{\rm WDM} = 3.5\,{\rm keV}}$$

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

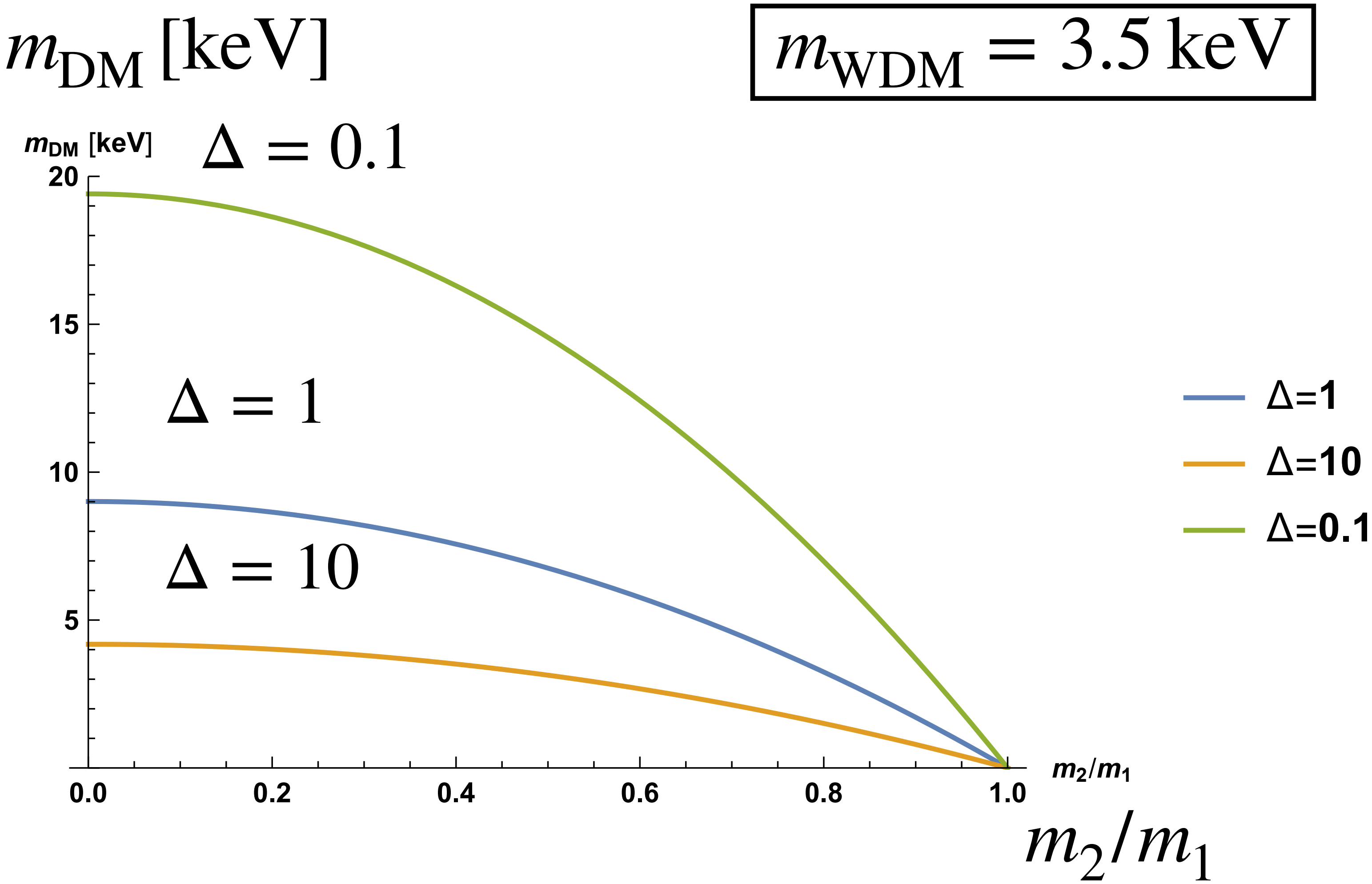
$$g_*(T_{\rm dec}) = 106.75$$

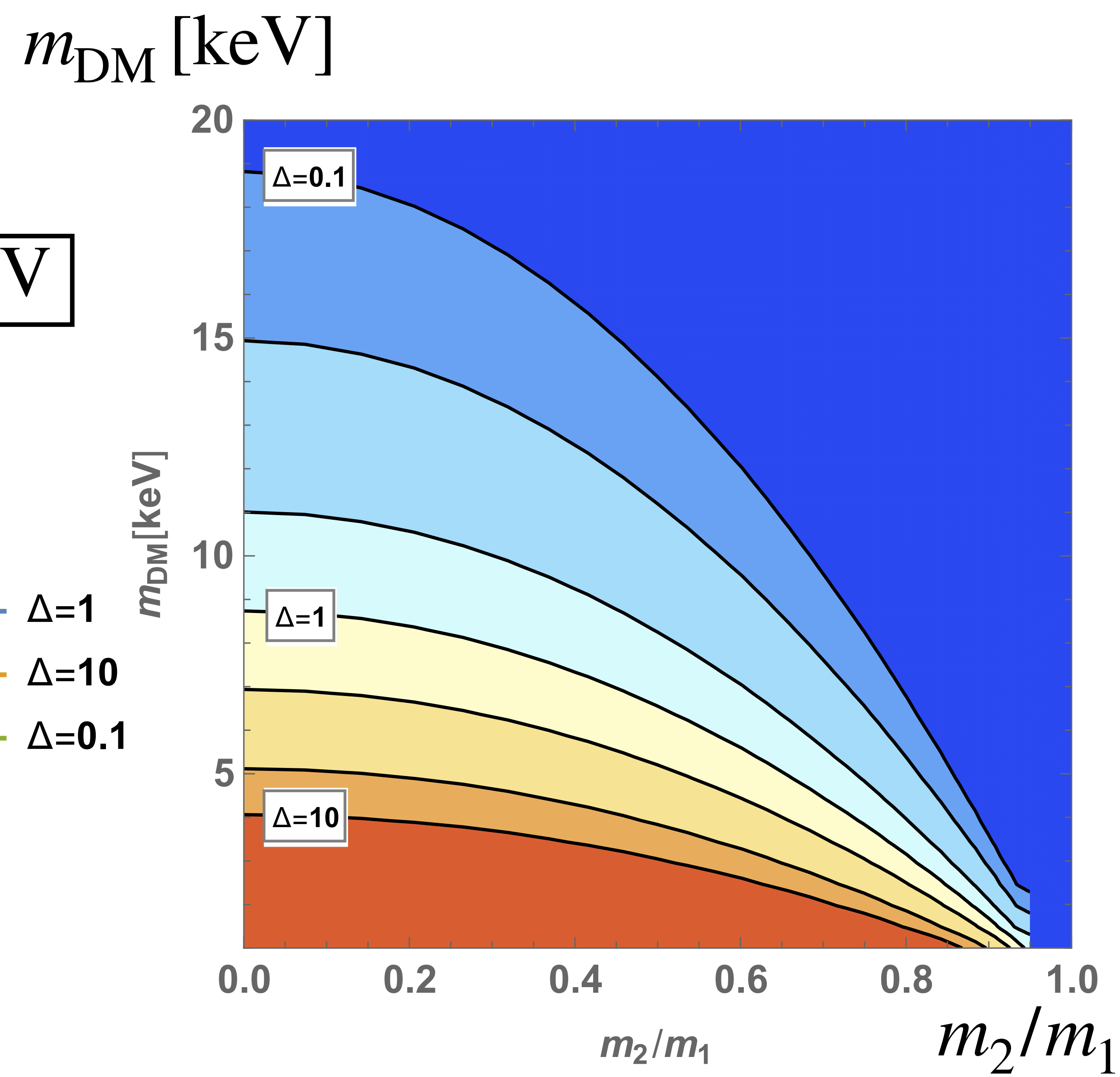




Analytic vs full

$m_{\mathrm{WDM}} = 3.5\,\mathrm{keV}$





Analytic mapping through warmness works well up to ~10% in m_{DM}

Part 3: More generic approach

Single parameter:

Viel, Lesgourgues, Haehnelt, Matarrese, and Riotto, PRD, 2005

$$P_{\rm WDM}/P_{\rm CDM} = T^2_{\rm WDM}(k) = \left[1 + (\alpha k)^{2\nu}\right]^{-10/\nu} \quad \nu = 1.12$$

$$\alpha = 0.049\,{\rm Mpc}/h \left(\frac{m_{\rm WDM}}{\rm keV}\right)^{-1.11} \left(\frac{\Omega_{\rm WDM}}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22}$$

Three parameters:

Murgia, Merle, Viel, Totzauer, and Schneider, JCAP, 2017

$$P_{\rm WDM}/P_{\rm CDM} = T^2_{\rm WDM}(k) = \left[1 + (\alpha k)^{\beta}\right]^{2\gamma}$$

(α, β, γ) - covers not only FIMPs, but also a broad class of DM models

e.g., Fuzzy DM, Interacting DM

Boehm, Fayet, and Schaeffer, PLB, 2001

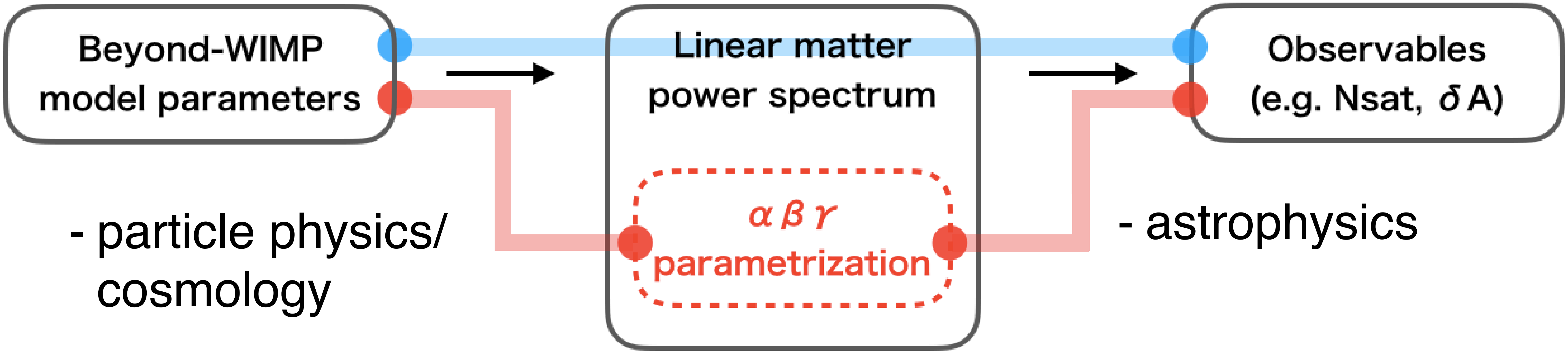
Hu, Barkana, and Gruzinov, PRL, 2000

Hui, Ostriker, Tremain, and Witten, PRD, 2017

ETHOS collaboration, PRD, 2016 and MNRAS, 2016

Two-step approach

Bae, Jinno, AK, and Yanagi, in preparation

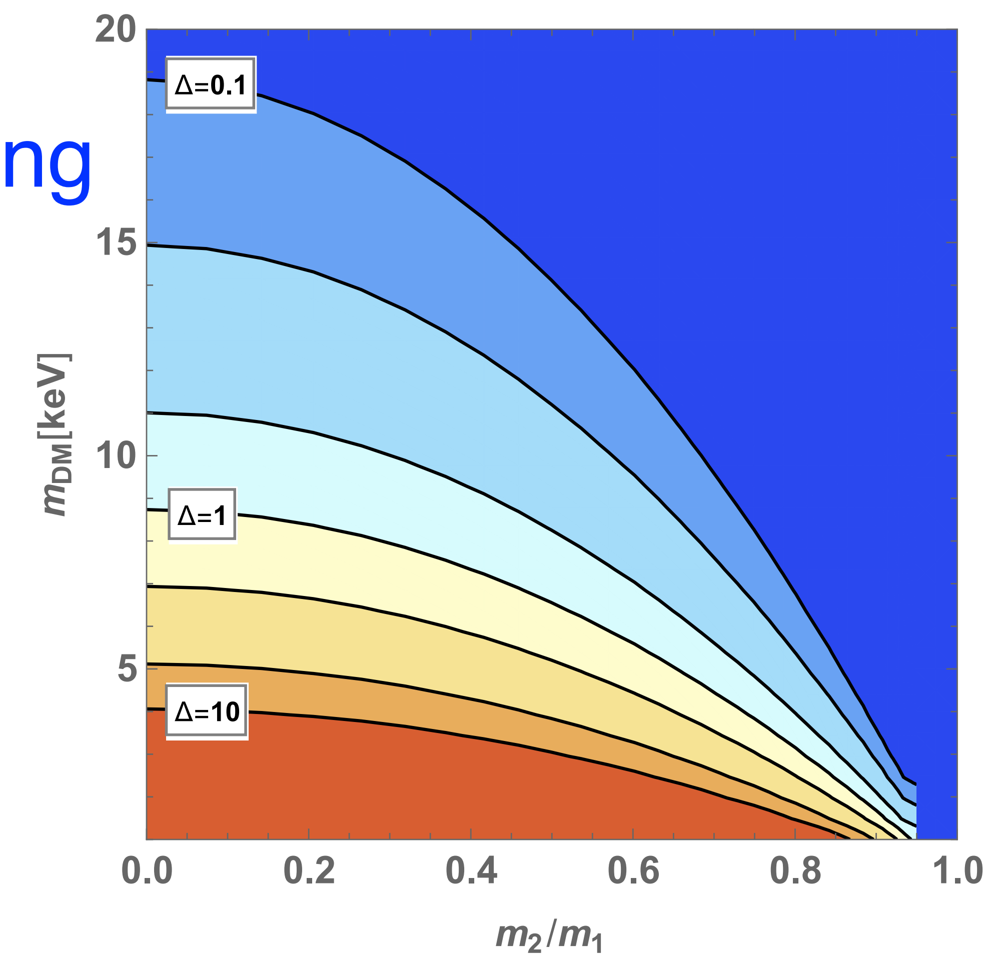


- particle physics/ cosmology

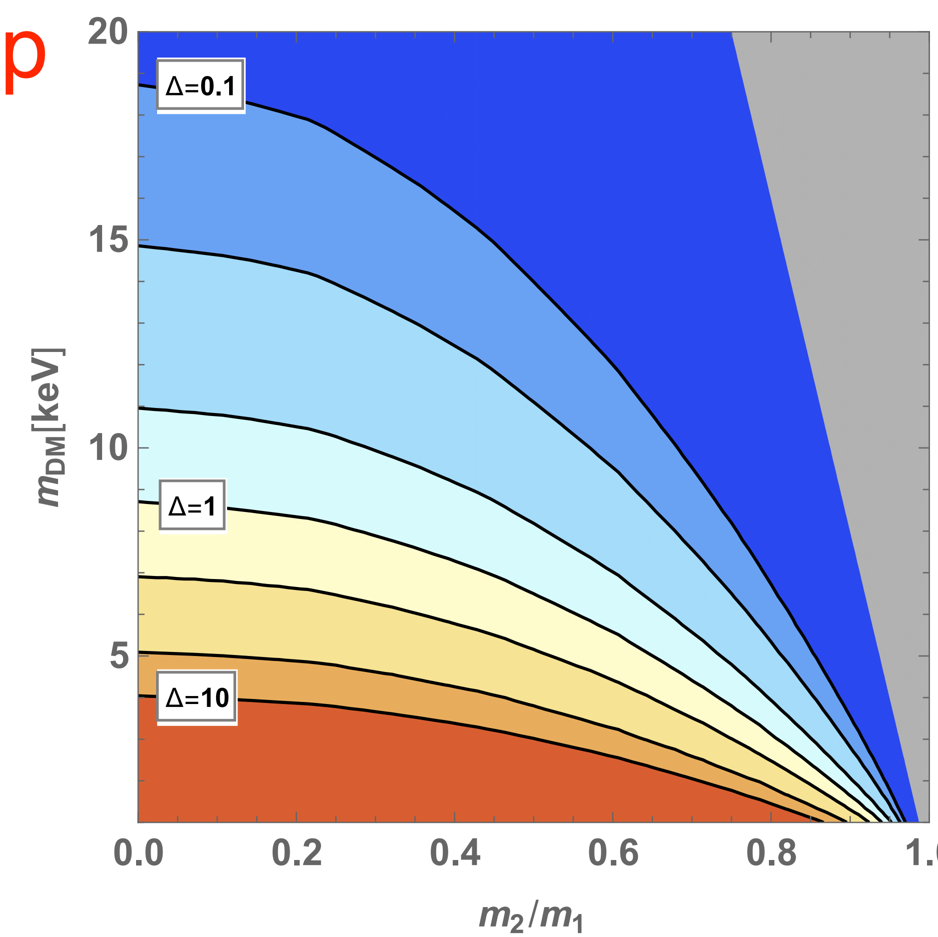
- astrophysics

Three parameters → not easy to share results → Machine learning!

- direct modeling



- two-step via ML



Summary

FIMPs are as a good benchmark as pragmatic WIMPs

- relic abundance insensitive to ultraviolet physics (early Universe dynamics)
- accommodated in well-motivated particle physics models

e.g., axino (SUSY partner of axion)

Light (keV-scale) FIMPs are of particular interest

- indirect detection experiments (3.5 keV X-ray line)
- galactic-scale structure formation (small-scale issues)

Summary

Once the mass is inferred by indirect detection experiments, we would like to check if FIMPs are consistent w/ galactic-scale structure formation

- conventional thermal WDM ≠ FIMP

- mapping from $m_{\rm WDM}$, e.g., through warmness σ^2

    - only phase-space distribution is needed

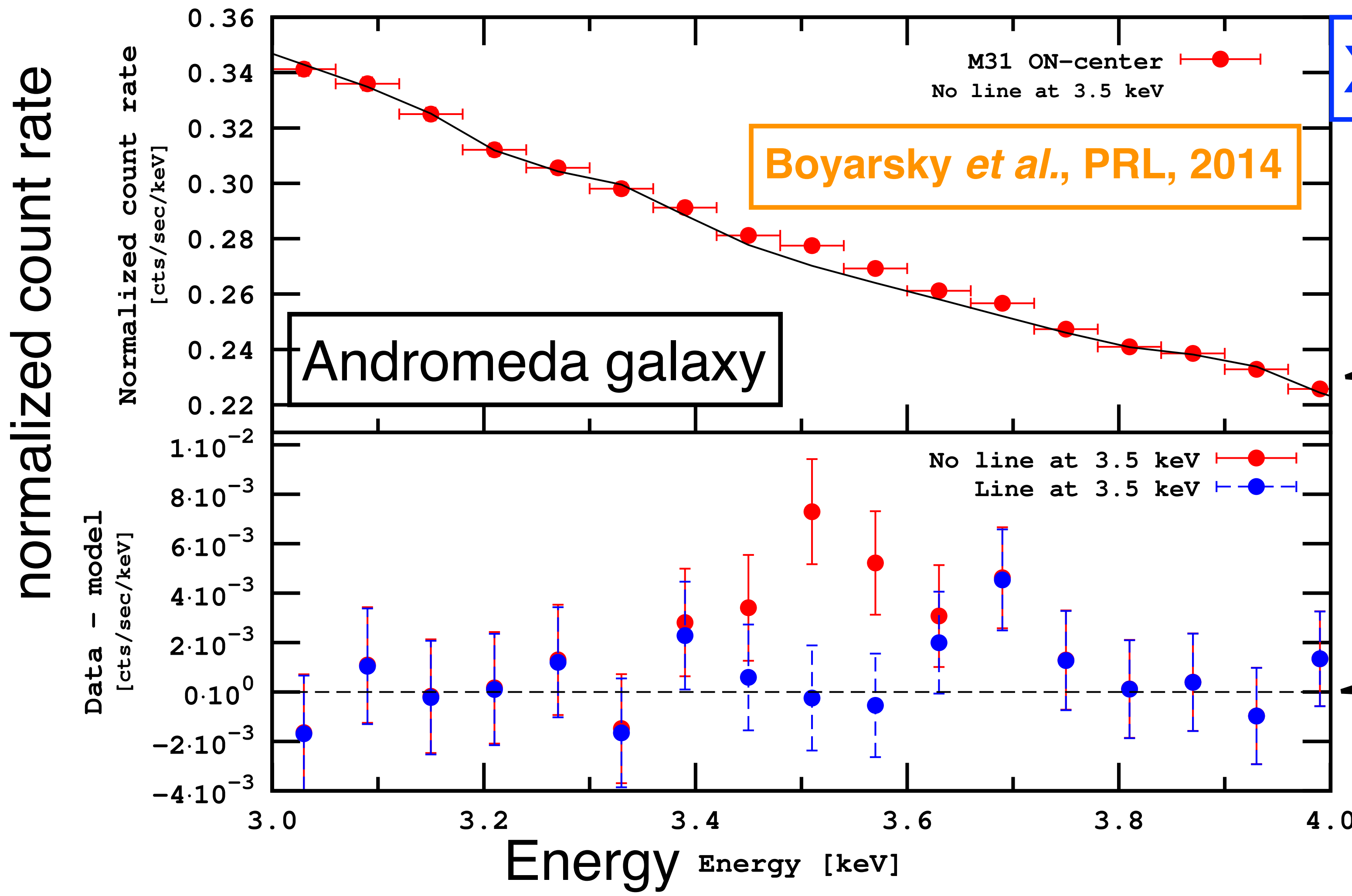
    - analytic formulas available in a simplified model

More generic approach w/ (α, β, γ) parametrization of $T^2(k)$
divide the task into two: particle physics part and astrophysics part

- Machine learning helps us share results with each other

Thank you for your attention

Anomalous line around 3.5 keV



XMM-Newton

continuum
(w/ instrumental)

+3.5 keV line

Chandra

Andromeda galaxy

Horiuchi *et al.*, PRD, 2014

null-detection

3.5 keV line excess is found in some instruments (Chandra, XMM-Newton), but not in others (Suzaku); in some objects (Galaxy clusters, Andromeda galaxy), but not in others (M31, dwarf spheroidal)

Sterile neutrino

Right-handed neutrino inferred by observed neutrino oscillations
- heavier than active ones through the see-saw mechanism

m_s : mass
θ : mixing angle

$m_s = 7\,\mathrm{keV}$
$\sin^2(2\theta) \sim 10^{-10}$

radiative decay $\tau \sim 10^{27}\,\mathrm{s}$ through $\mathcal{L}_{\rm int} \propto \sin(2\theta) e G_{\rm F} m_s \nu_s \sigma^{\mu\nu} \nu_a F_{\mu\nu}$

$\nu_s \to \nu + \gamma$

X-ray

produced around the QCD phase transition through the mixing with active neutrinos:

$$\Omega_s h^2 \simeq 0.01 \left(\frac{\sin^2 2\theta}{2\times 10^{-10}}\right)\left(\frac{m_s}{7\,\mathrm{keV}}\right)^2 \ll \Omega_{\rm dm} h^2 \simeq 0.12$$

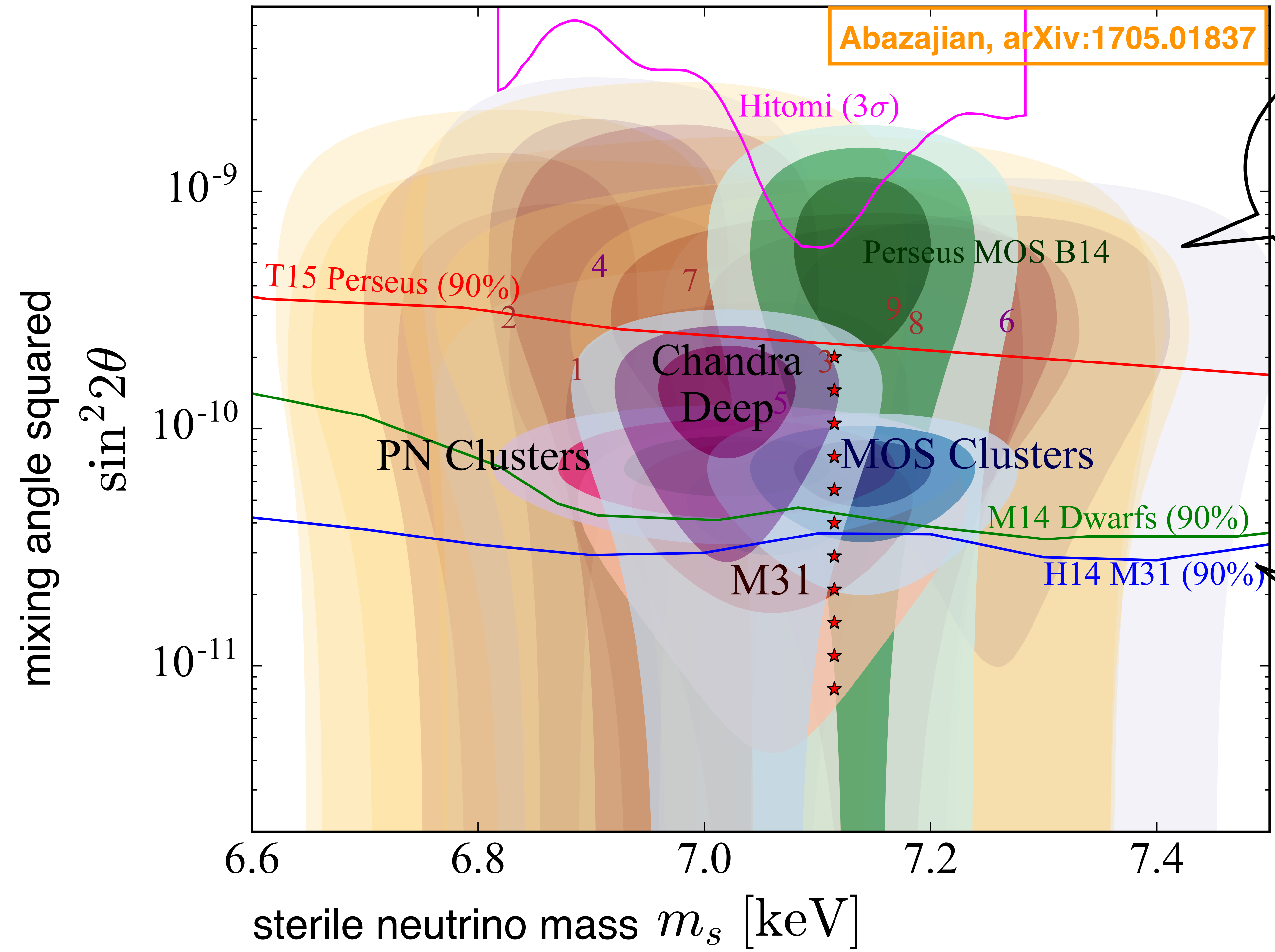
Dodelson *et al.*, PRL, 1994
Abazajian *et al.*, PRD, 2006
Asaka *et al.*, JHEP, 2007

The mixing may be enhanced by a large lepton asymmetry:

$$\frac{n_\ell}{s} \sim 10^{-6} \quad \text{c.f.} \quad \frac{n_b}{s} \simeq 9\times 10^{-11}$$

Shi *et al.*, PRL, 1999
Abazajian *et al.*, PRL, 2014

3.5 keV line status



shaded regions: preferred from 3.5 keV excess

lines: constraints from null-detection

A large part of preferred parameter region (including a central value) has been disfavored by null-detections, although not covered

Axion

Strong CP-problem:

$$\mathcal{L}_{CP} = \bar{\theta}\frac{g_3^2}{32\pi^2}G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}, \quad \bar{\theta} = \theta - \arg\det Y_u - \arg\det Y_d$$

neutron electric dipole moment → $|\bar{\theta}| \lesssim 10^{-10}$

Baker *et al.*, PRL, 2006

A solution: **Peccei-Quinn (PQ) symmetry**

Peccei *et al.*, PRL, 1977

Peccei *et al.*, PRD, 1977

Weinberg, PRL, 1978

Wilczek, PRL, 1978

- anomalous: $\bar{\theta} \to \bar{\theta} + \alpha$
- spontaneous symmetry breaking → axion

$$\mathcal{L}_{CP} = \left(\bar{\theta} + \frac{a}{f_a}\right)\frac{g_3^2}{32\pi^2}G^a_{\mu\nu}\widetilde{G}^{a\,\mu\nu}, \quad \bar{\theta} + \langle a/f_a\rangle = 0$$

Prominent realizations:

- Kim-Shifman-Vainstein-Zakharov (KSVZ): vector-like heavy quarks are charged under PQ-symmetry

Kim, PRL, 1979 | Shifman *et al.*, Nucl. Phys. B, 1980

- DFSZ: SM quarks are charged under PQ-symmetry

Dine *et al.*, PLB, 1981 | Zhitnitsky, Sov. J. Nucl. Phys. B, 1980

Supersymmetry (SUSY)

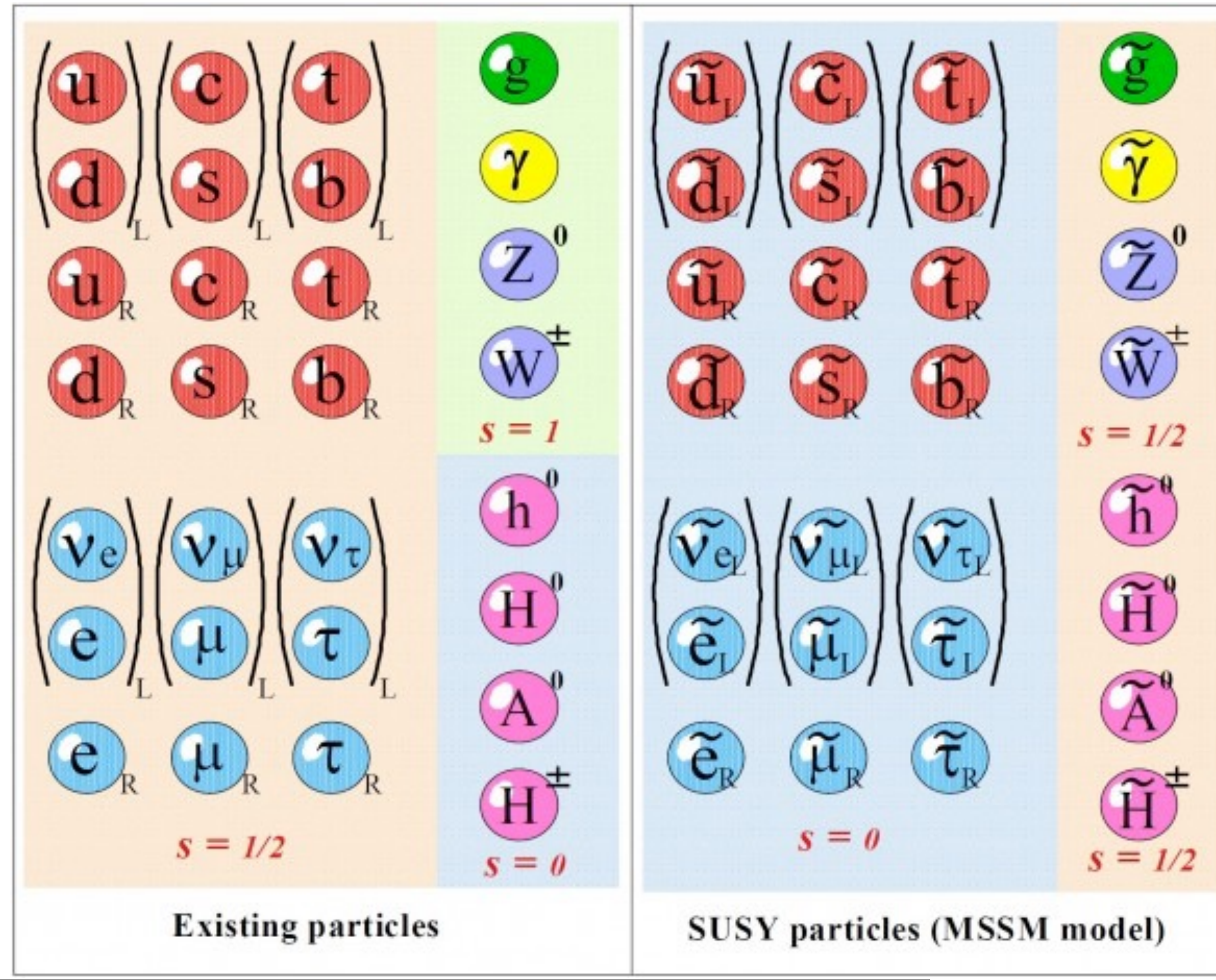
Nontrivially extended Poincaré symmetry:
Boson ↔ Fermion

$$A = \frac{s + ia}{\sqrt{2}} + \sqrt{2}\theta\tilde{a} + \theta^2 \mathcal{F}_A$$

saxion

axino

Martin, arXiv:hep-ph/9709356



supersymmetric extension of the SM: MSSM

→ achieve grand unification

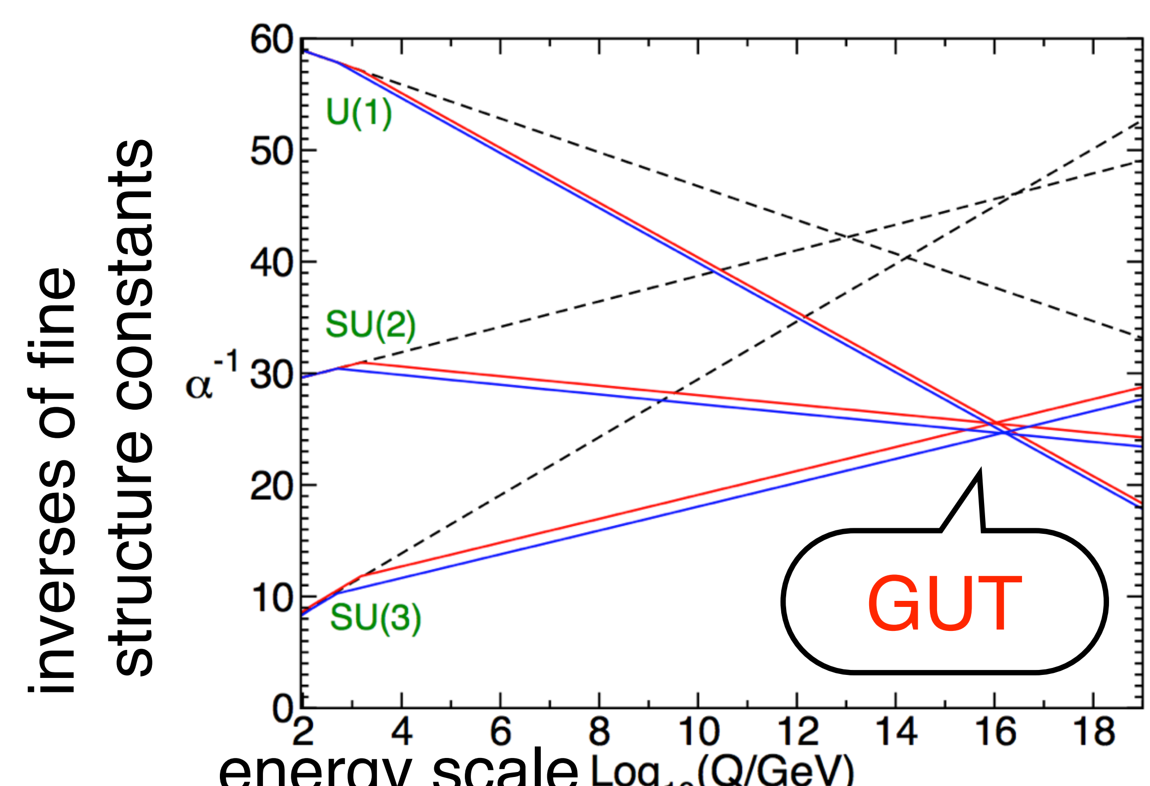
→ solve the **large hierarchy problem**

$$m^2_{h^0} = m^2_{h^0,0} + \Delta(m^2_{h^0})$$

model prediction $(126\ \mathrm{GeV})^2$

model parameter

quantum correction $\sim(10^{17}\ \mathrm{GeV})^2$



Properties of SUSY axion

Saxion and axino masses:
axion is (almost) massless
→ saxion and axino are massless in the SUSY limit
SUSY breaking ($m_{3/2}$) → naively $m_s \sim m_{\tilde{a}} \sim m_{3/2}$
depending on models $m_s \sim m_{3/2}$, $m_{\tilde{a}} \sim m_{3/2}^2 / f_a$

Goto *et al.*, PLB, 1992
Chun *et al.*, PLB, 1992
Chun *et al.*, PLB, 1995

$m_{3/2} \sim 100\,\mathrm{GeV}$, $f_a \sim 10^{10}\,\mathrm{GeV}$ → $m_{\tilde{a}} \sim 1\,\mathrm{keV}$

PQ scale constraint:

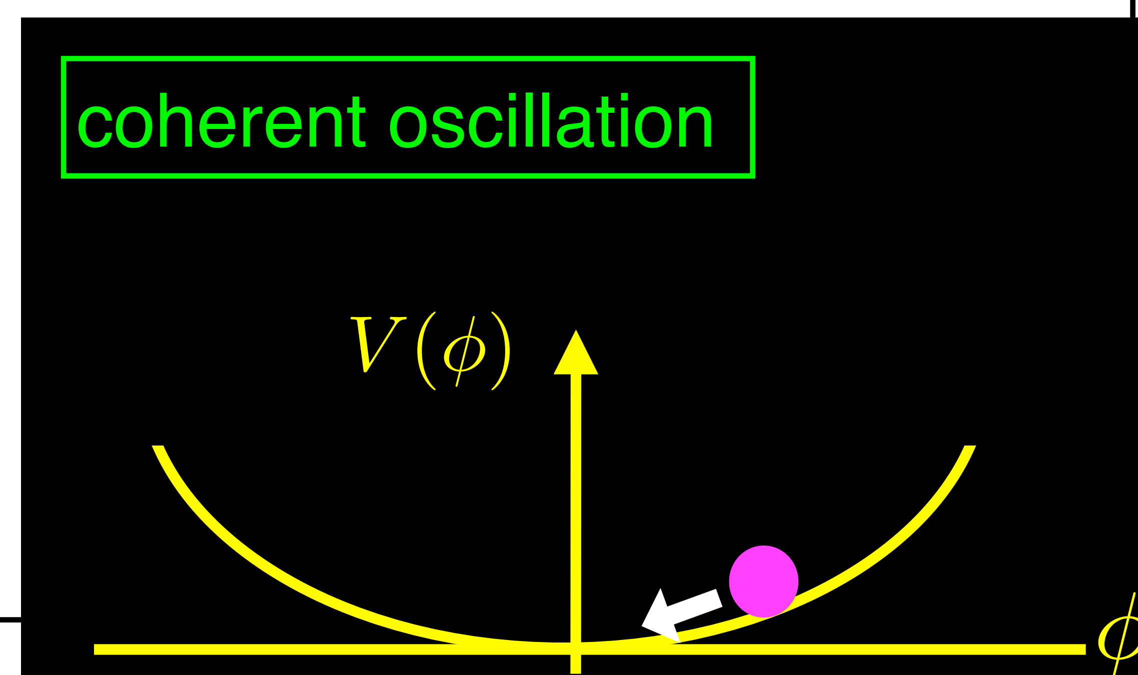
Raffelt, Lect. Notes Phys., 2008

- supernova cooling (SN1987A) through nucleon bremsstrahlung
→ $f_a > 4 \times 10^8\,\mathrm{GeV}$
- axion coherent oscillation

$$\Omega_a h^2 \simeq 0.11 \left(\frac{f_a}{5 \times 10^{11}\,\mathrm{GeV}} \right)^{1.19} F \bar{\theta}_{\mathrm{i}}^2$$

$$\ll \Omega_{\mathrm{dm}} h^2 \simeq 0.12$$

Bae *et al.*, JCAP, 2008
Wants *et al.*, PRD, 2010



μ term and R-parity violating term

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

$$Q_{\rm PQ}(L_i) = 2$$

Kim *et al.*, PLB, 1984

Chun, PLB, 1999 | Choi *et al.*, PRD, 2001 | Chun, JHEP, 2006

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

$$W_{\rm bRPV} = \frac{y_i'}{M_*^2} X^3 L_i H_u$$

cut-off scale

$$X = \frac{v_{\rm PQ}}{\sqrt{2}} e^{A/v_{\rm PQ}} \quad , \quad v_{\rm PQ} = f_a N_{\rm DW}$$

$N_{\rm DW} = 6$ (DFSZ)

spontaneous PQ symmetry breaking

μ term and bilinear R-parity violating (bRPV) term:

$$W_{\rm eff} = \mu H_u H_d + \epsilon_i \mu L_i H_u$$

$M_* \sim 10^{16}\,{\rm GeV}$, $v_{\rm PQ} \sim 10^{10}\,{\rm GeV}$, $y_0 \sim 0.1$, $y_i' \sim 1$

$\rightarrow$ $\mu \sim 500\,{\rm GeV}$, $\epsilon_i \sim 10^{-5}$

$m_s = 7\,{\rm keV}$

$\sin^2(2\theta) \sim 10^{-10}$

axino-neutrino mixing:

$$\theta \simeq 10^{-5} \left(\frac{\epsilon}{10^{-5}}\right) \left(\frac{\mu}{400\,{\rm GeV}}\right) \left(\frac{7\,{\rm keV}}{m_{\tilde a}}\right) \left(\frac{10^{10}\,{\rm GeV}}{v_{\rm PQ}}\right)$$

Axino production

Dodelson-Widrow mechanism:

$$\Omega_{\tilde{a}} h^2 \simeq 0.01 \left(\frac{\sin^2 2\theta}{2 \times 10^{-10}} \right) \left(\frac{m_{\tilde{a}}}{7\,\mathrm{keV}} \right)^2 \ll \Omega_{\rm dm} h^2 \simeq 0.12$$

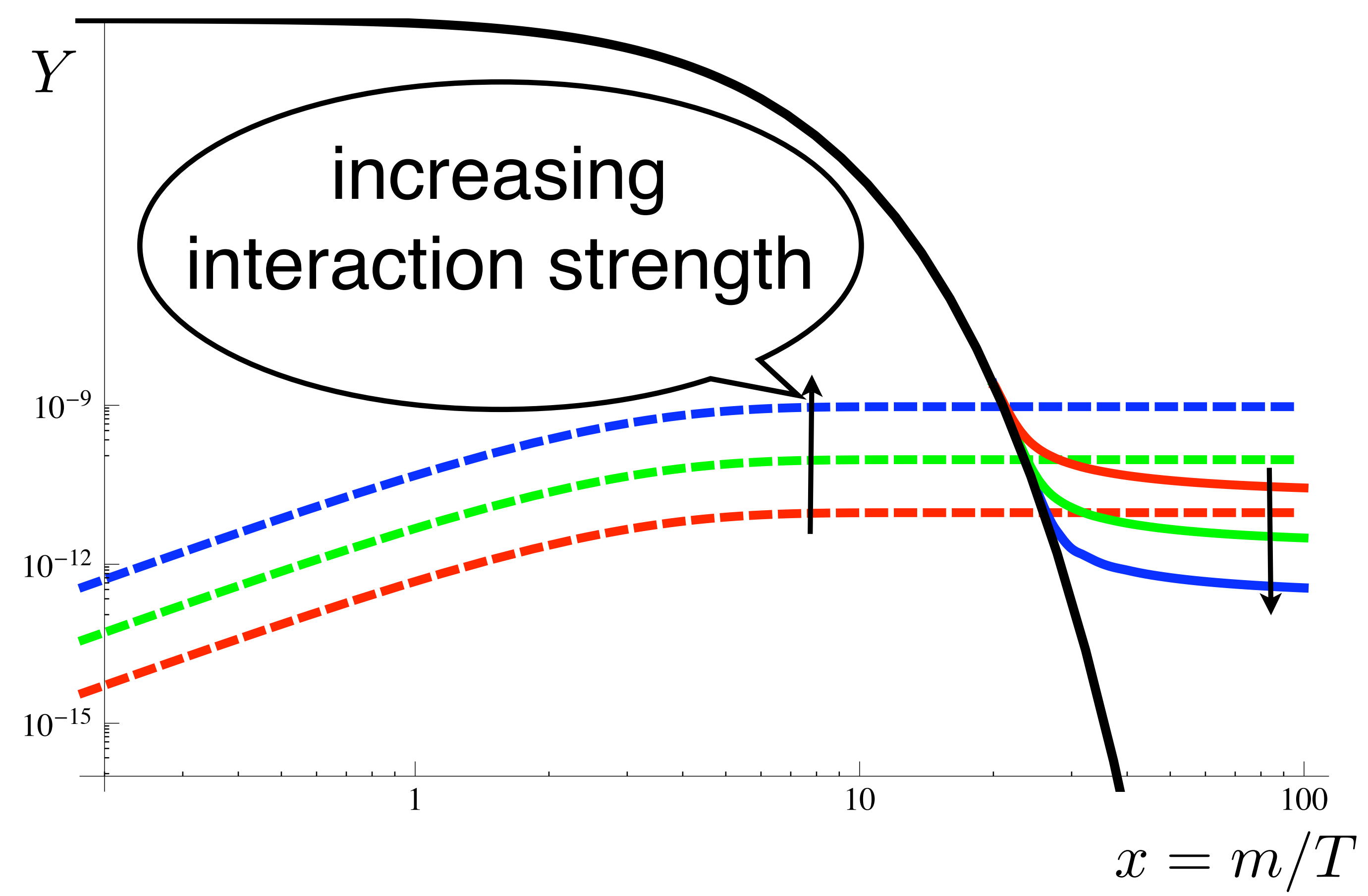
axino interacion: $W_{\rm int} = \frac{2\mu}{v_{\rm PQ}} A H_u H_d$

feeble
renormalizable
interaction

Hall *et al.*, JHEP, 2010

Freeze-in production of feebly interacting massive particles (FIMPs)

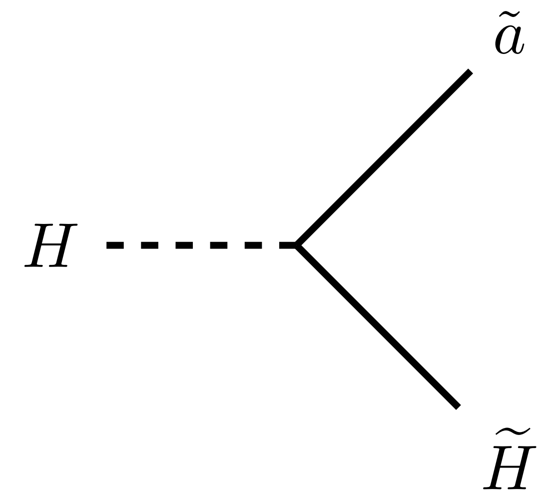
Never in thermal equilibrium
Yield per Hubble time $\Gamma_{\rm pro} Y_{\rm eq}/H$
increases with decreasing T
until the Boltzmann suppression
$Y_{\rm eq} \propto \exp(-m/T)$



Production processes

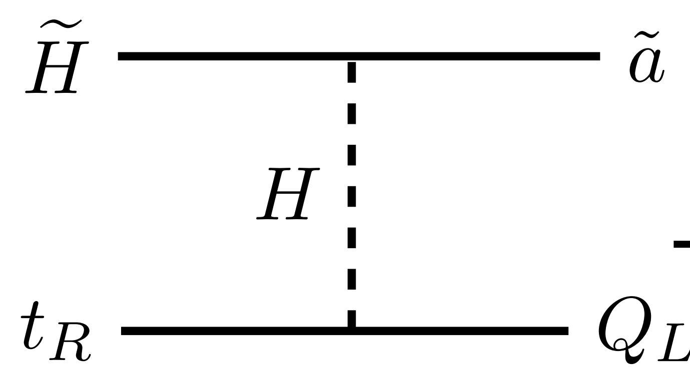
2-body decay of Higgs or Higgsino:

freeze-in at $T \sim m_H$ or μ



scatterings of Higgsino through lighter Higgs:

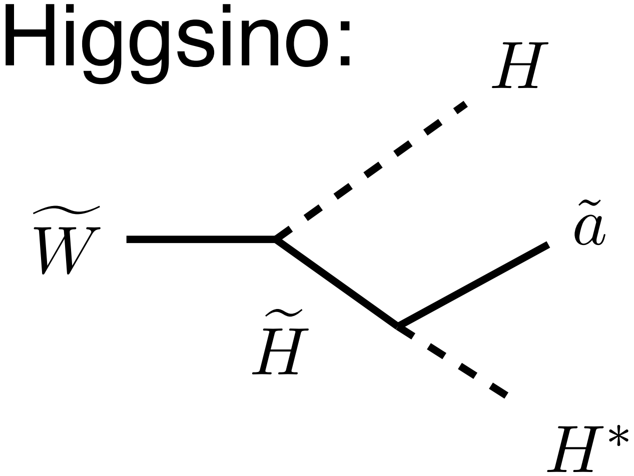
freeze-in at $T \sim \mu$



+ s-channel

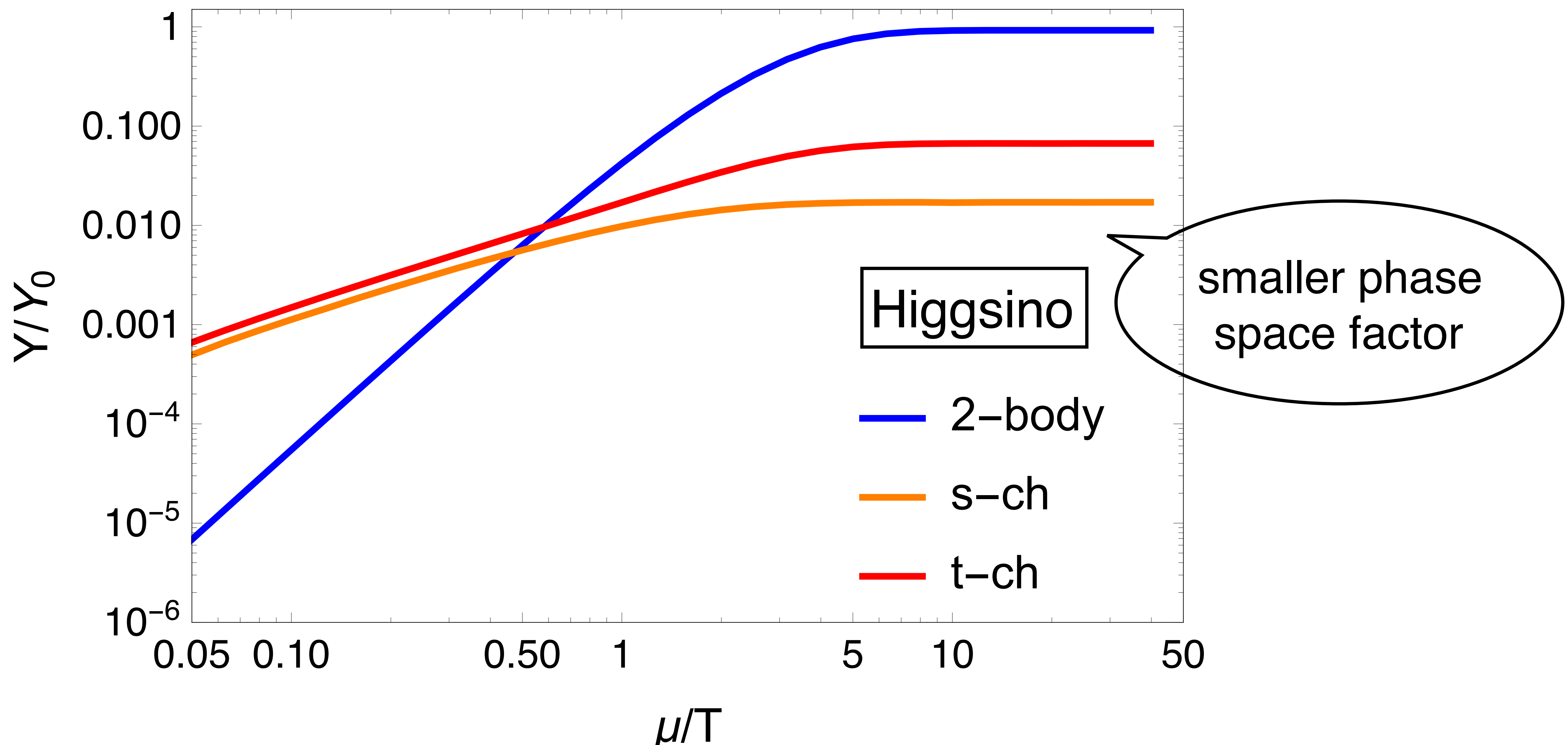
3-body decay of wino through heavier Higgsino:

freeze-in at $T \sim M_2$



Yield from each process

reaction rate per Hubble time: $\Gamma_{\rm pro} Y_{\rm eq}/H$, $H \propto T^2$
decay: $\Gamma_{\rm pro} \sim (m/T)\Gamma_{\rm dec}$
scattering through a renormalizable interaction: $\Gamma_{\rm pro} \propto T$



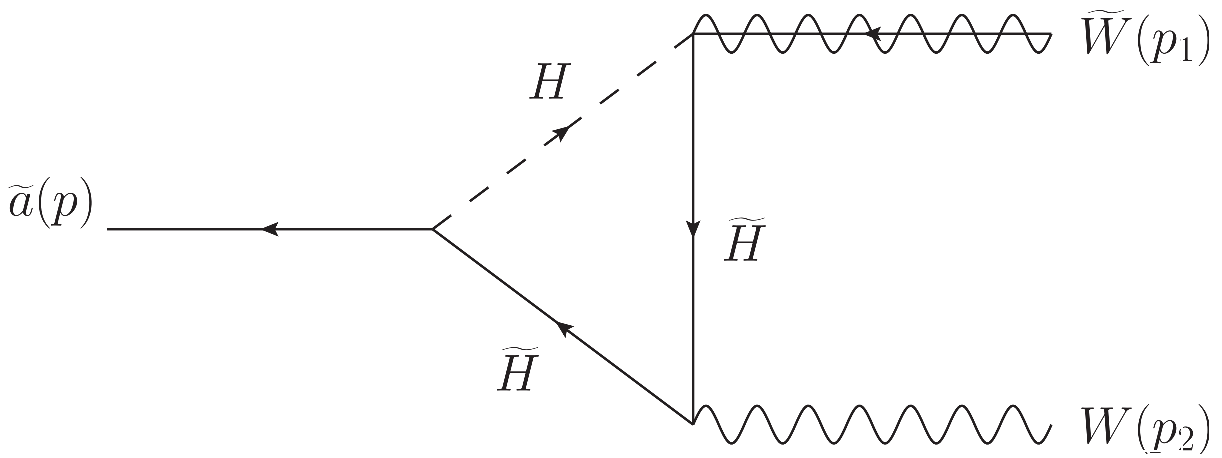
Freeze-in: $\Omega_{\tilde{a}} h^2 \simeq 0.5 \left(\frac{\mu}{500\,\mathrm{GeV}}\right) \left(\frac{2.5\times 10^{10}\,\mathrm{GeV}}{v_{\rm PQ}}\right)^2 \left(\frac{m_{\tilde{a}}}{7\,\mathrm{keV}}\right)$

Anomalous coupling

Low energy anomalous coupling
- non-decoupling term (cut-off scale is not manifest)

$$\mathcal{L} \supset -\frac{g_3^2}{32\pi^2 v_{\rm PQ}/N_{\rm DW}} \int d^2\theta A W^a W^a + \text{h.c.}$$

one particle irreducible (1PI) diagram



$\propto \dfrac{\mu^2}{p^2}$ for $p^2 \gg \mu^2$

Bae *et al.*, JHEP, 2011 | Bae *et al.*, JCAP, 2012

Anomalous couplings are just loop-suppressed contribution and negligible for axino production
↔ big difference from the KSVZ model

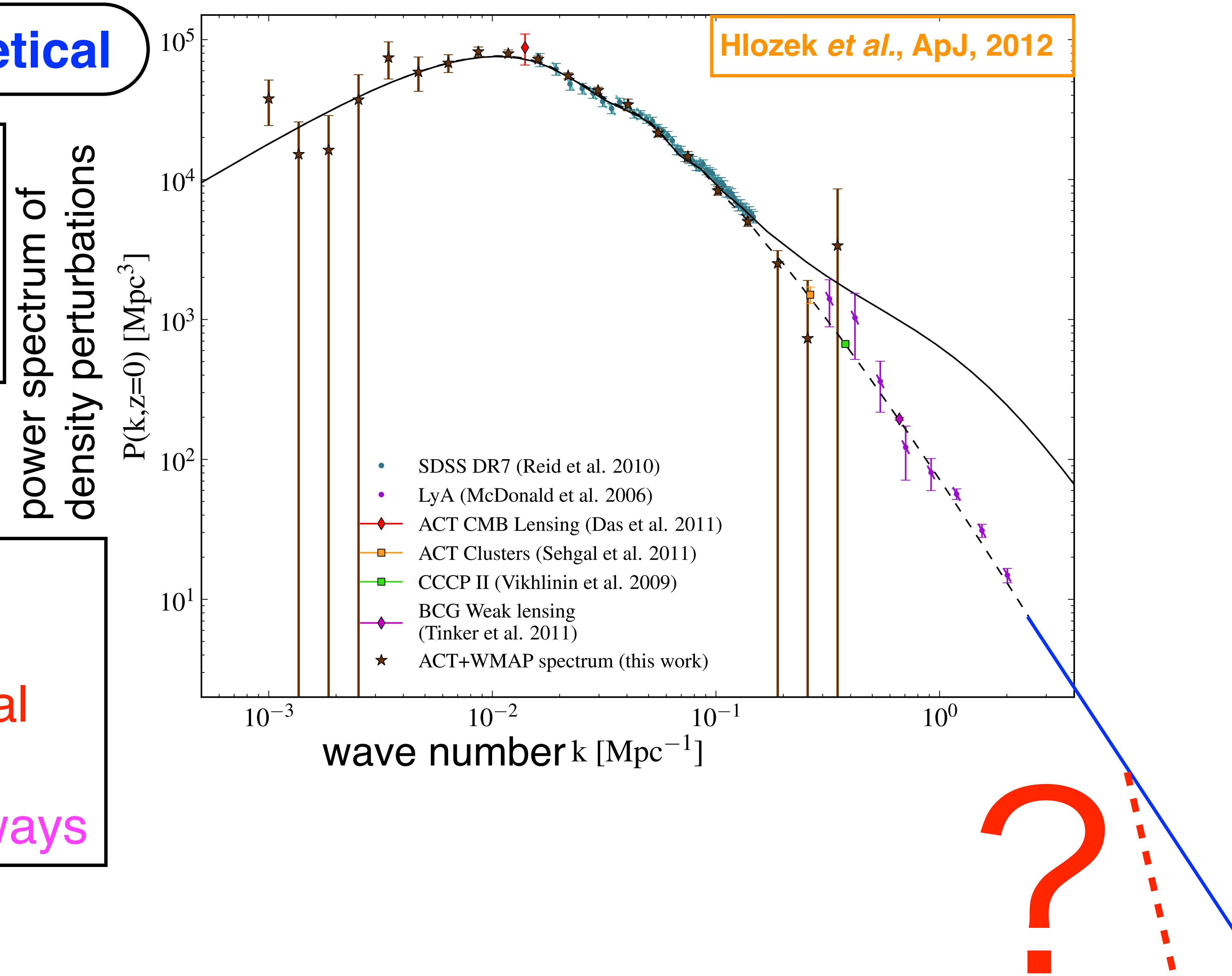
Cold Dark Matter?

hypothetical

cold dark matter:
null thermal velocity
only gravitationally interacting

↕

particle physics DM candidates:
finite (sizable) thermal velocity
interacting in many ways



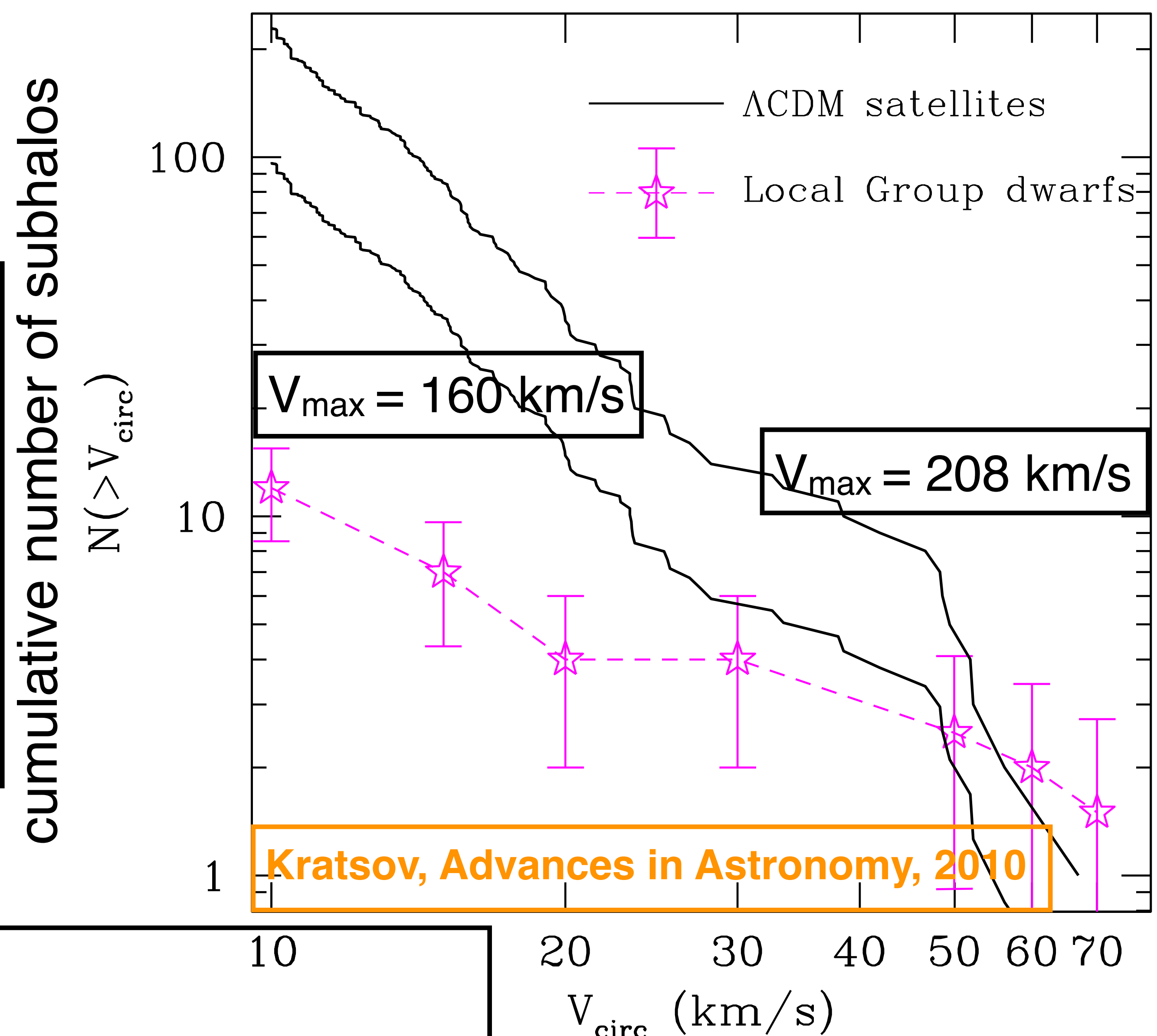
Small scale matter density fluctuations, especially their deviations from the ΛCDM model, contain imprints of the nature of DM

Small scale crisis I

When *N*-body simulations in the ΛCDM model and observations are compared, problems appear at (sub-)galactic scales: **small scale crisis**

missing satellite problem

N-body (DM-only) simulations in the ΛCDM model → Milky Way-size halos host O(10) times larger number of subhalos than that of observed dwarf spheroidal galaxies



maximal circular velocity of subhalo

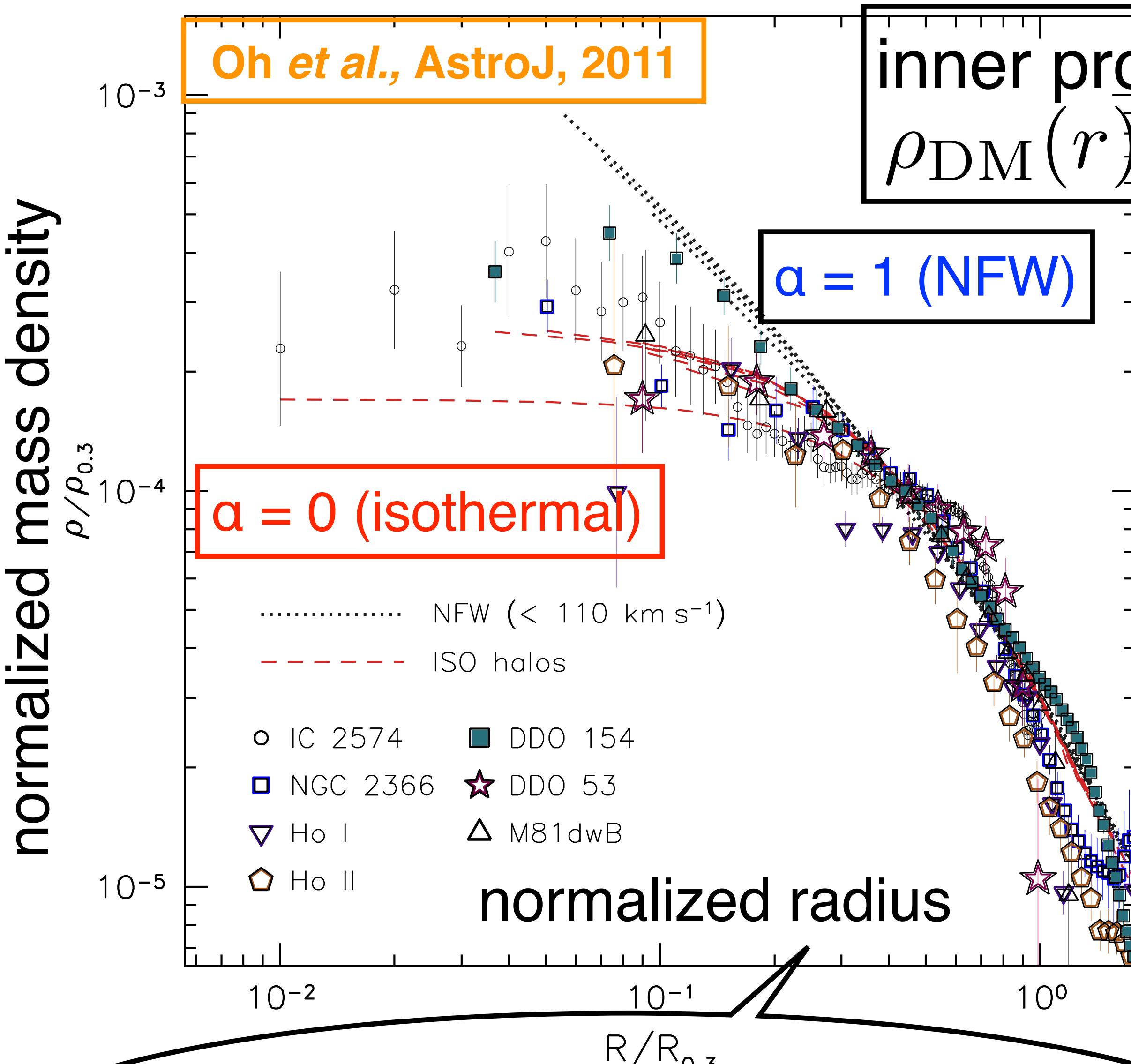
(maximum) circular velocity

$$V_{\rm circ}^2(r) = \frac{GM(<r)}{r} \qquad V_{\rm max} = \max_r \{V_{\rm circ}(r)\}$$

Small scale crisis II

cusp vs core problem

N-body (DM-only) simulations in the ΛCDM model → common DM profile independent of halo size: NFW profile



inner profile:
$\rho_{\rm DM}(r) \propto r^{-\alpha}$

Observations infer cored profile in the inner region rather than cuspy NFW profile

field dwarf spheroidal galaxies
~10^9 Msun

NFW profile:

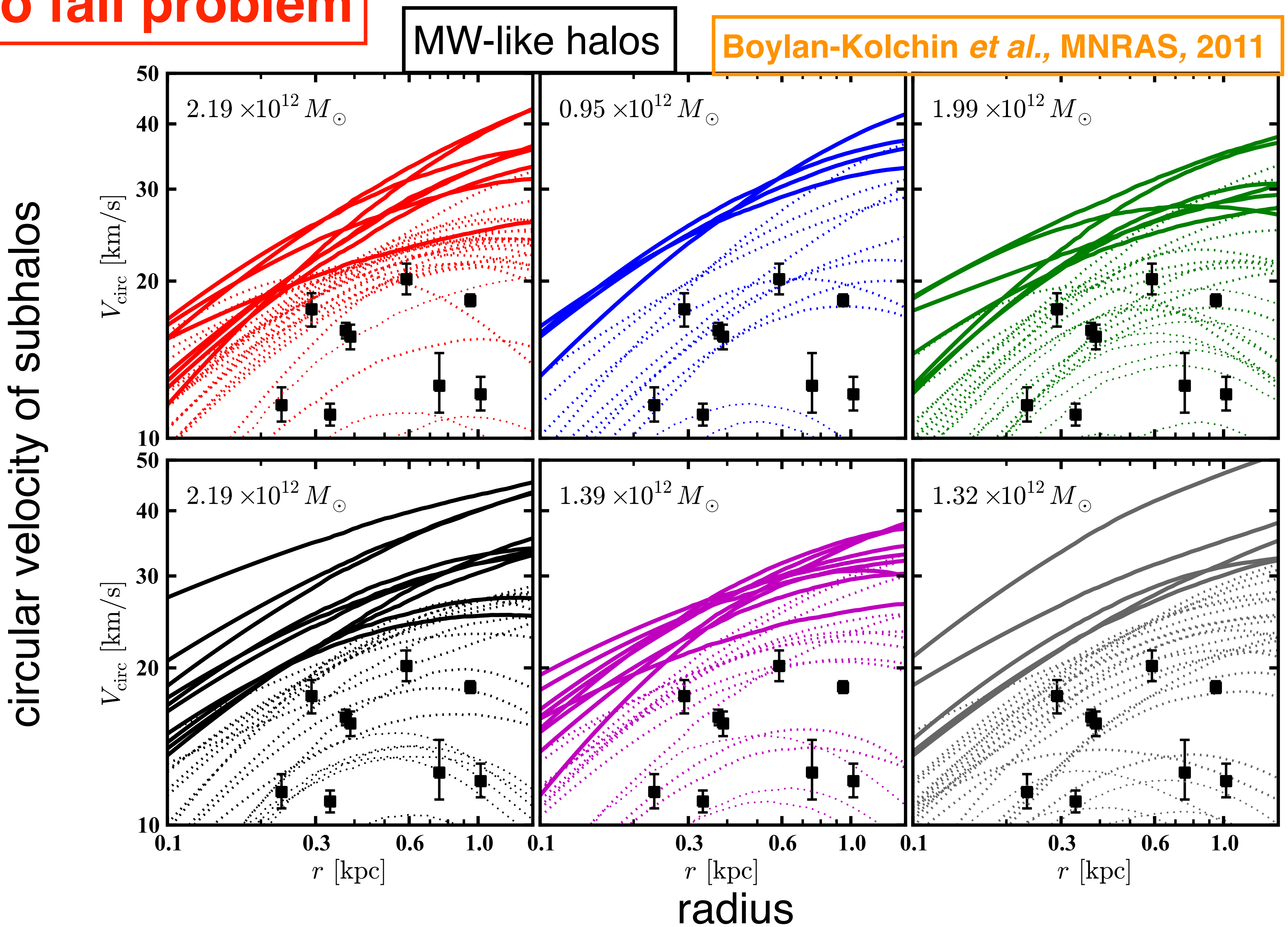
$$\rho_{\rm DM}(r) = \frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

isothermal profile:

$$\rho_{\rm DM}(r) = \rho_{\rm DM}^0 \begin{cases} 1 \ (r \ll r_0) \\ (r_0/r)^2 \ (r \gg r_0) \end{cases}$$

Small scale crisis III

too big to fail problem



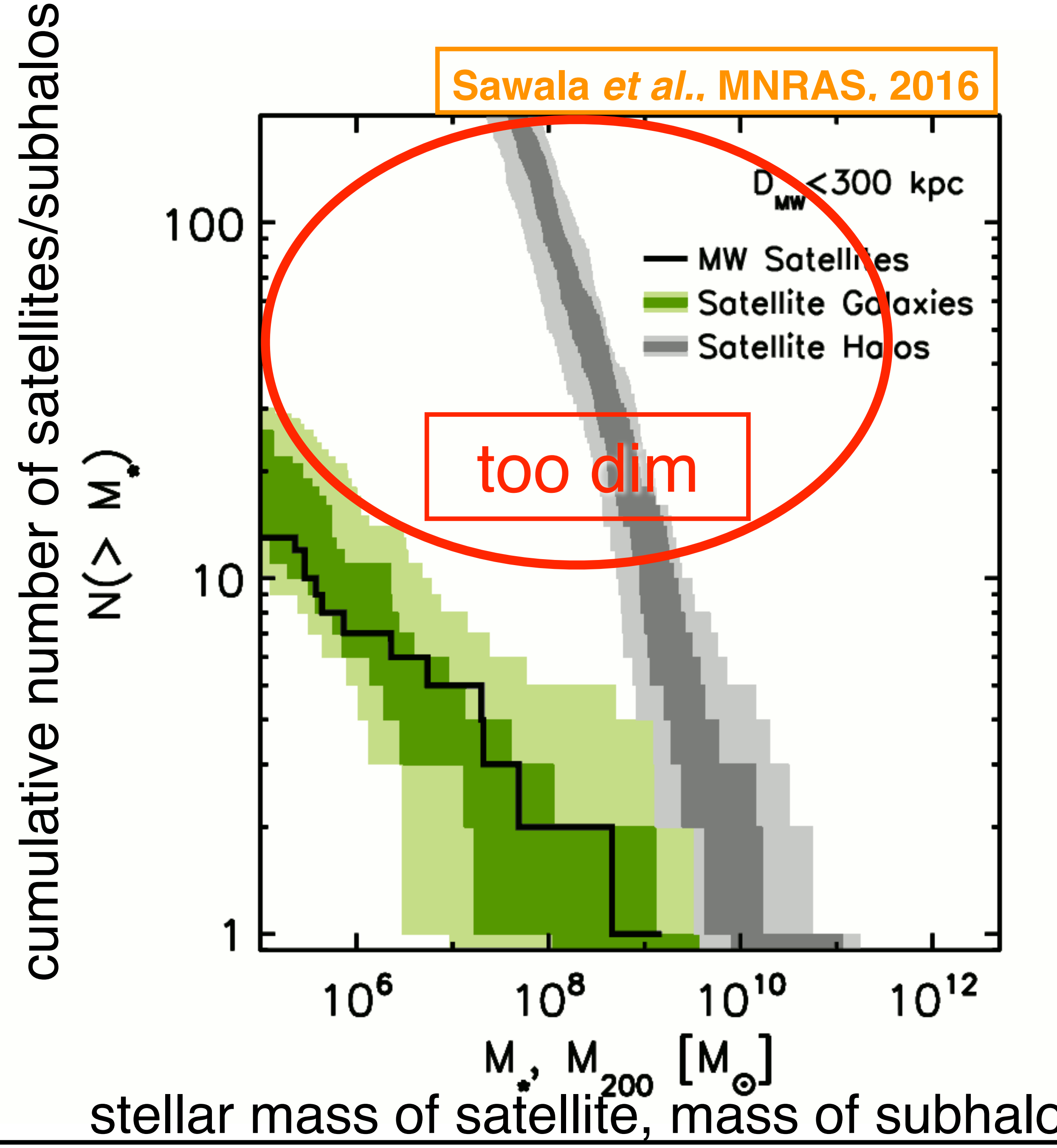
N-body (DM-only) simulations in the ΛCDM model →
~10 subhalos with deepest potential wells in Milky Way-size halos
do not host observed counterparts (dwarf spheroidal galaxies)

Possible solution I

Above Discussions are based on *N*-body (DM-only) simulations in the ΛCDM model

↕

Gravitational potentials are shallower for smaller objects → Baryonic heating and cooling may be dominant



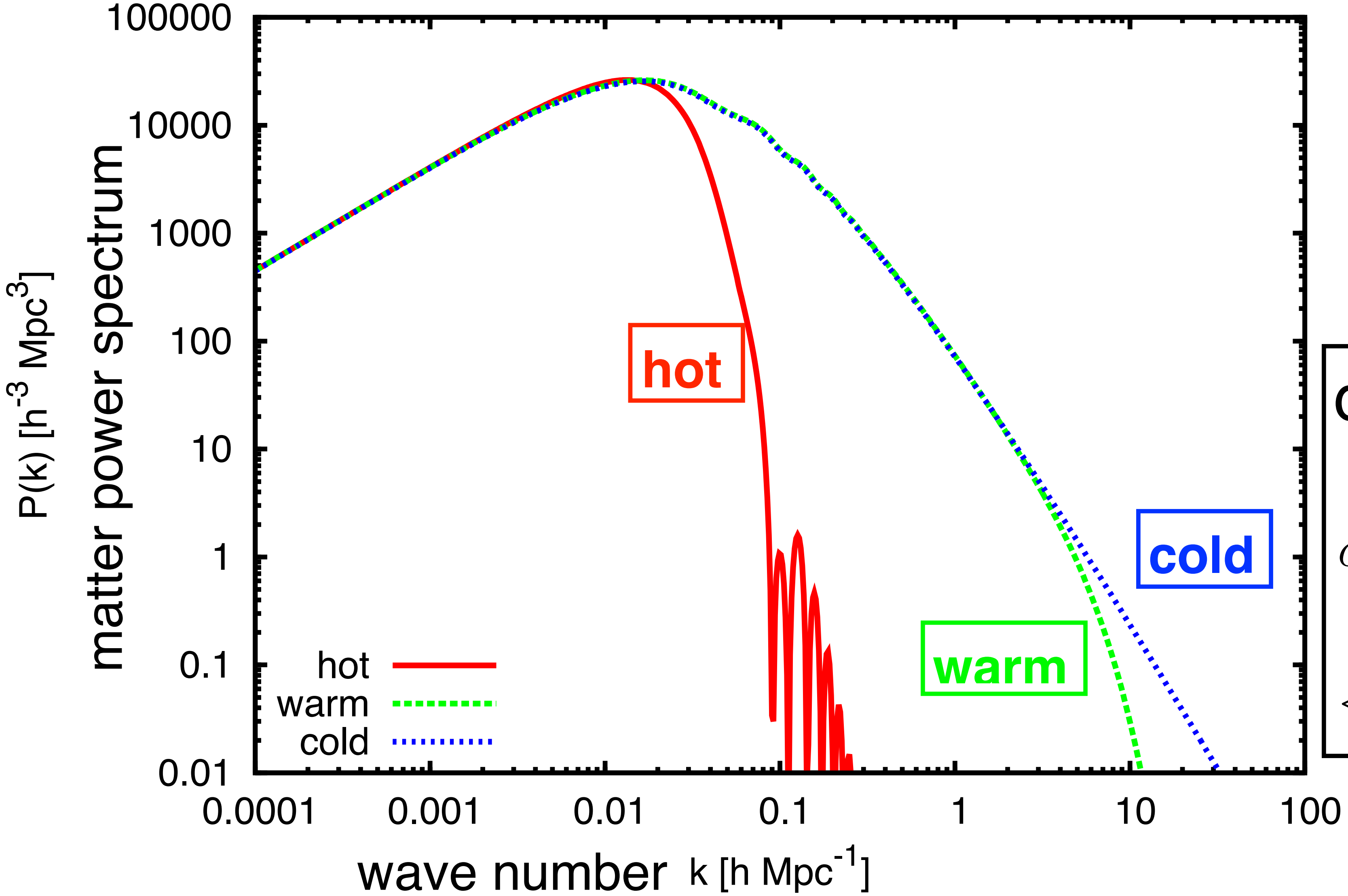
Baryonic processes

- heating from ionizing photons - ionizing photons emitted and spread around reionization of the Universe heat and evaporate gases

- mass loss by supernova explosions - supernova explosions blow gases from inner region → DM redistribute along shallower potential

Warm Dark Matter

Free-streaming of DM particles smears the small-scale primordial density fluctuations
Warm Dark Matter (WDM): the free-streaming length ~ **kpc - Mpc**
c.f. (in my personal experience)
Hot Dark Matter (HDM): the free-streaming length ~ Mpc - Gpc
Cold Dark Matter (CDM): the free-streaming length is below kpc



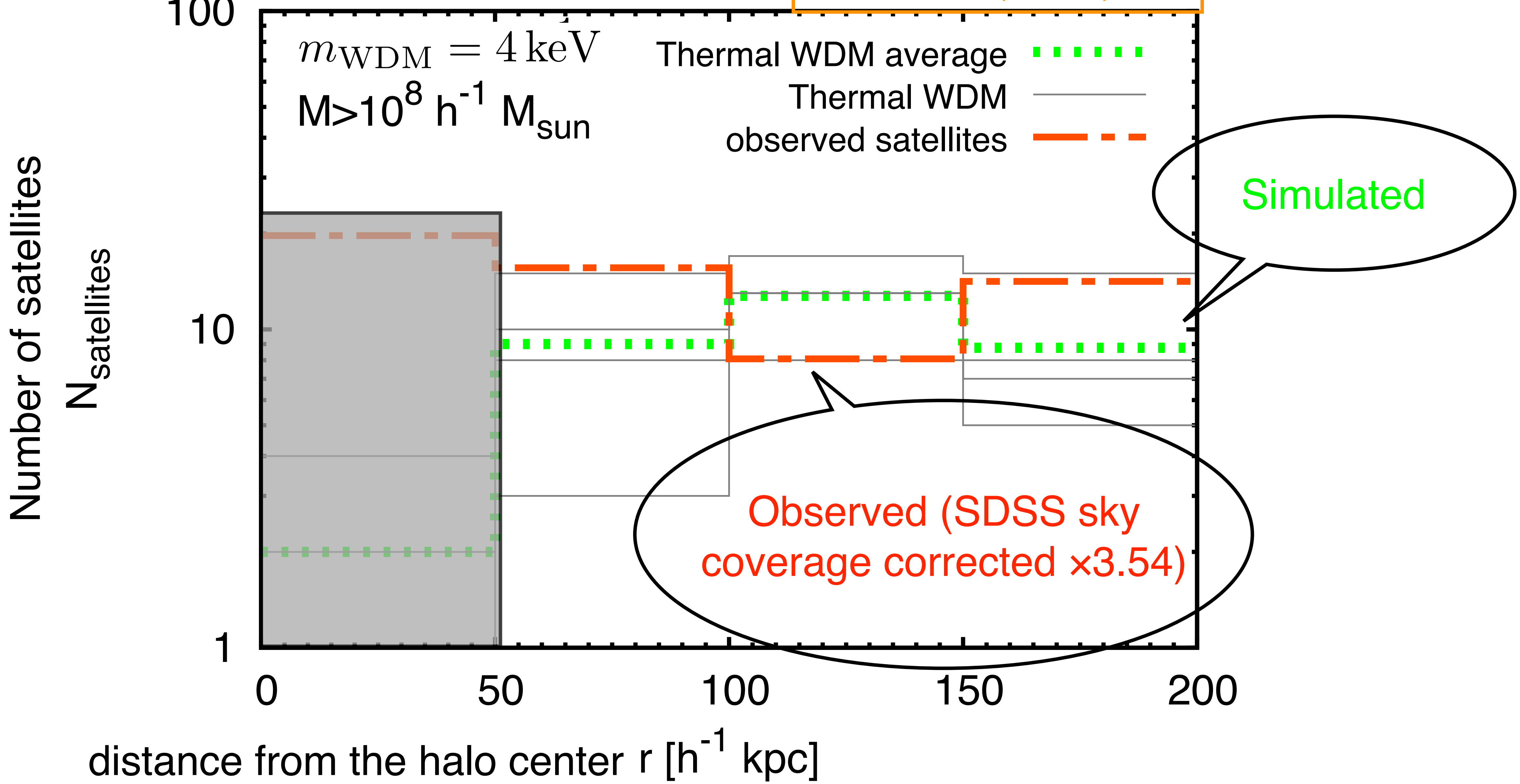
density perturbation

$$\delta(\mathbf{x}) \equiv \frac{\delta\rho}{\rho}(\mathbf{x}) = \int \frac{d\mathbf{k}^3}{(2\pi)^3}\delta(\mathbf{k})e^{i\mathbf{k}\mathbf{x}}$$

$$< \delta(\mathbf{k})\delta^*(\mathbf{k}') >= (2\pi)^3\delta^3(\mathbf{k}-\mathbf{k}')\mathrm{P}(\mathbf{k})$$

WDM subhalo number in a MW-like halo

Kamada *et al.*, JCAP, 2013



N-body (DM-only) simulations in ΛWDM model

→ suppressed number of subhalos

$m_{\rm WDM} = 1\text{–}2\,{\rm keV}$ (w/o SDSS sky coverage corrected)

$m_{\rm WDM} = 2\text{–}4\,{\rm keV}$ (w SDSS sky coverage corrected)

is preferred if each subhalo hosts an observable galaxy

Polisensky *et al.*, PRD, 2011

Kamada *et al.*, JCAP, 2013

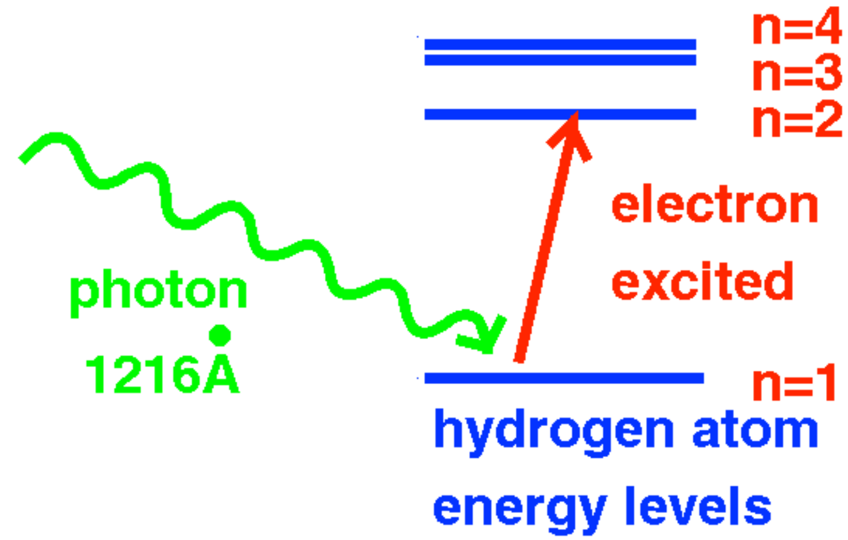
Lovell *et al.*, MNRAS, 2014

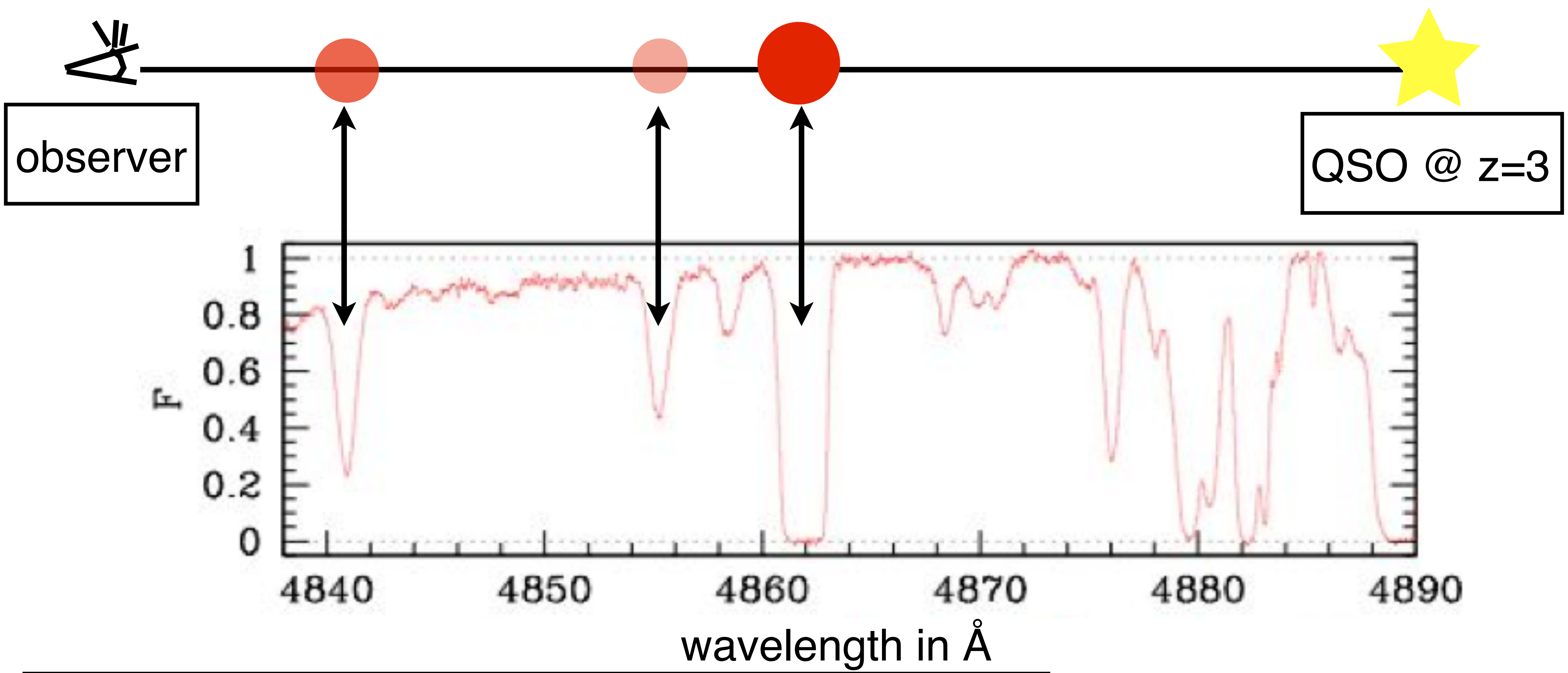
Kennedy *et al.*, MNRAS, 2014

Horiuchi *et al.*, PRD, 2014

Lyman-alpha forest as a probe of matter distribution

absorption intensity/frequency
$\leftrightarrow$ HI distribution along the line-of-sight

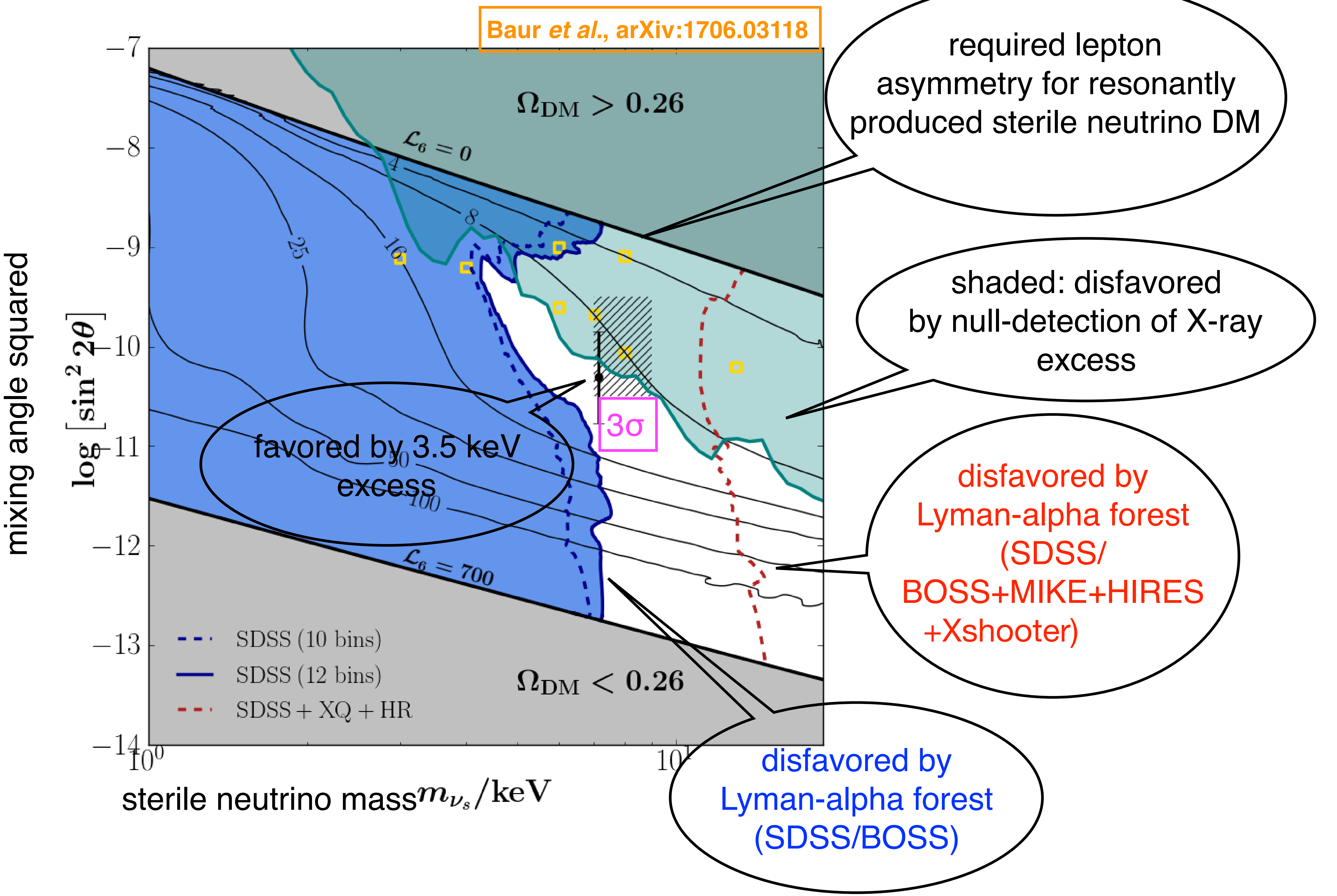




normalized flux $\mathrm{F} = e^{-\tau}$

optical depth $\tau \propto \left(\frac{\rho_{\mathrm{HI}}}{\bar{\rho}}\right)^{\alpha}$ $\alpha \simeq 1.6 - 2.4$

Sterile neutrino parameter space

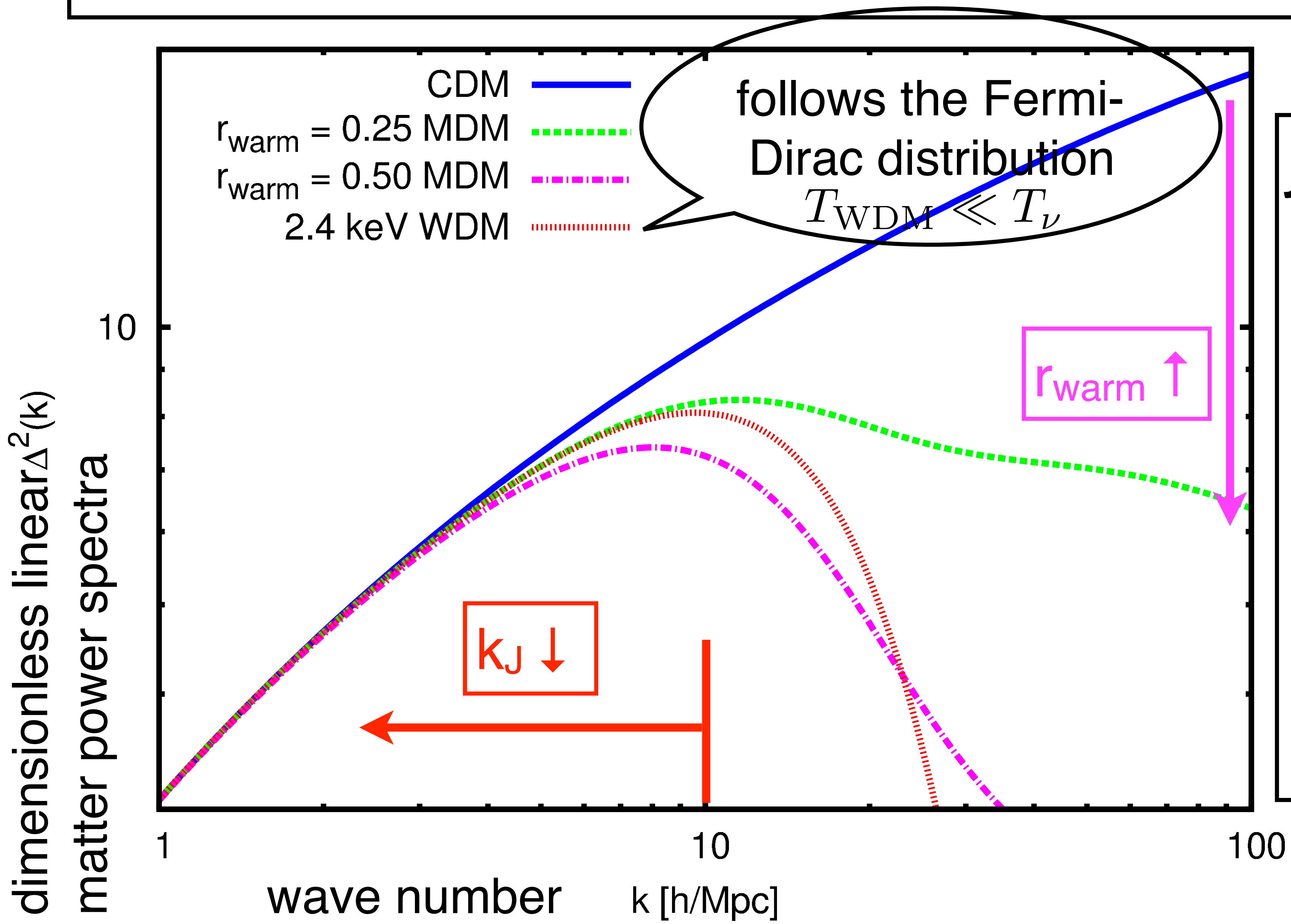


Sterile neutrino as mixed dark matter

proportional to the Fermi-Dirac distribution $T_s = T_\nu$

sterile neutrino (WDM) relic (from the Dodelson-Widrow mechanism) accounts for **20-60%** of DM mass density (rest: CDM) → CDM+WDM=**MDM**

Harada, AK, JCAP, 2016



Jeans scale at the matter-radiation equality:

velocity dispersion of MDM

$$k_{\rm J} = a\sqrt{\frac{4\pi G\rho_{\rm m}}{\sigma^2}}\Bigg|_{t=t_{\rm eq}}$$

$$= 64\,{\rm Mpc}^{-1}\left(\frac{m_{\rm WDM}}{2.4\,{\rm keV}}\right)^{4/3}\left(\frac{1}{r_{\rm warm}}\right)^{5/6}$$

$$= 64\,{\rm Mpc}^{-1}\left(\frac{m_s}{7\,{\rm keV}}\right)\left(\frac{0.25}{r_{\rm warm}}\right)^{1/2}$$

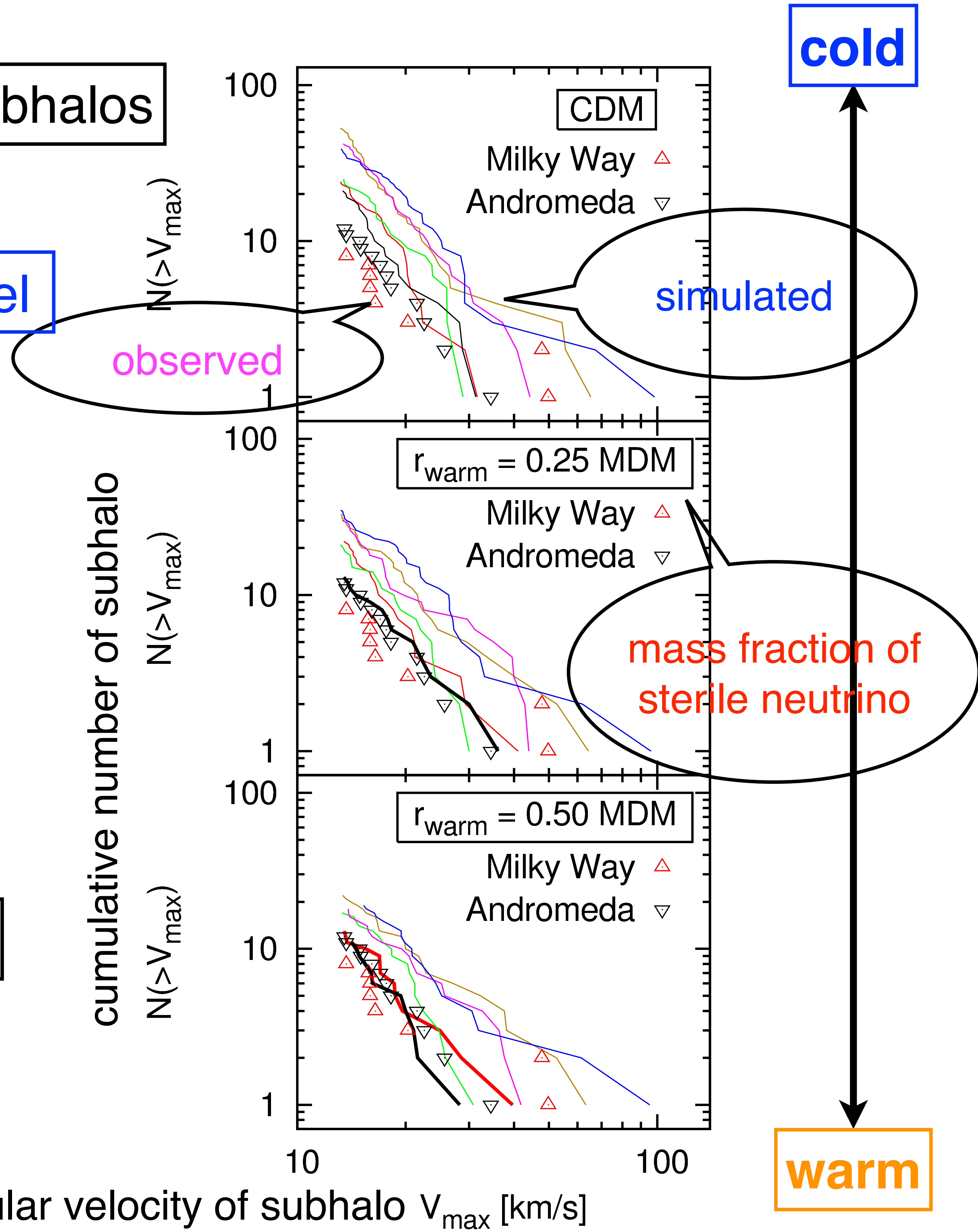
MDM subhalo number in a MW-like halo

cumulative velocity function of subhalos

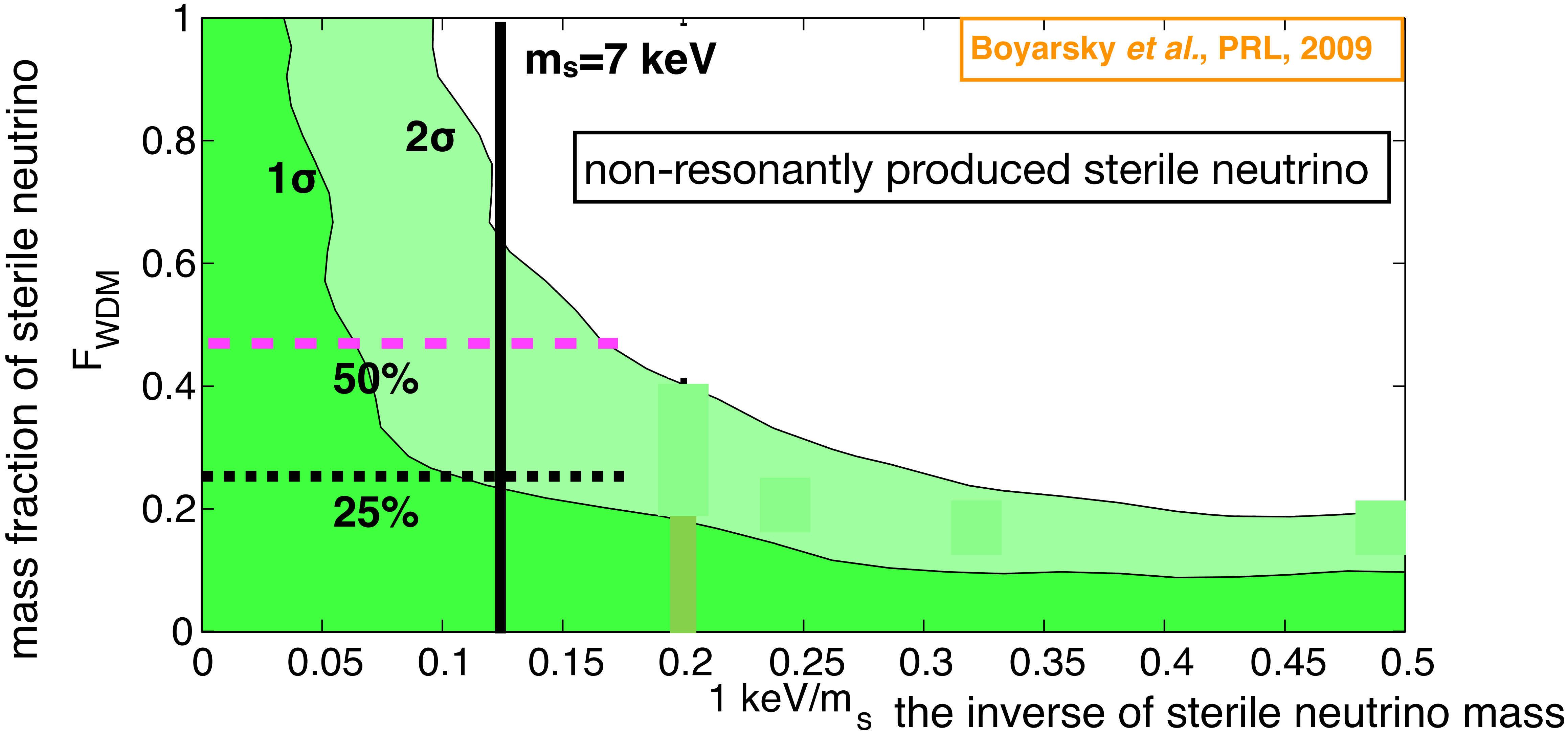
Too many subhalos in CDM model

1 out of 6 halos may reproduce the number of observed dwarf spheroidal galaxies

2 out 6 halos appear concordant

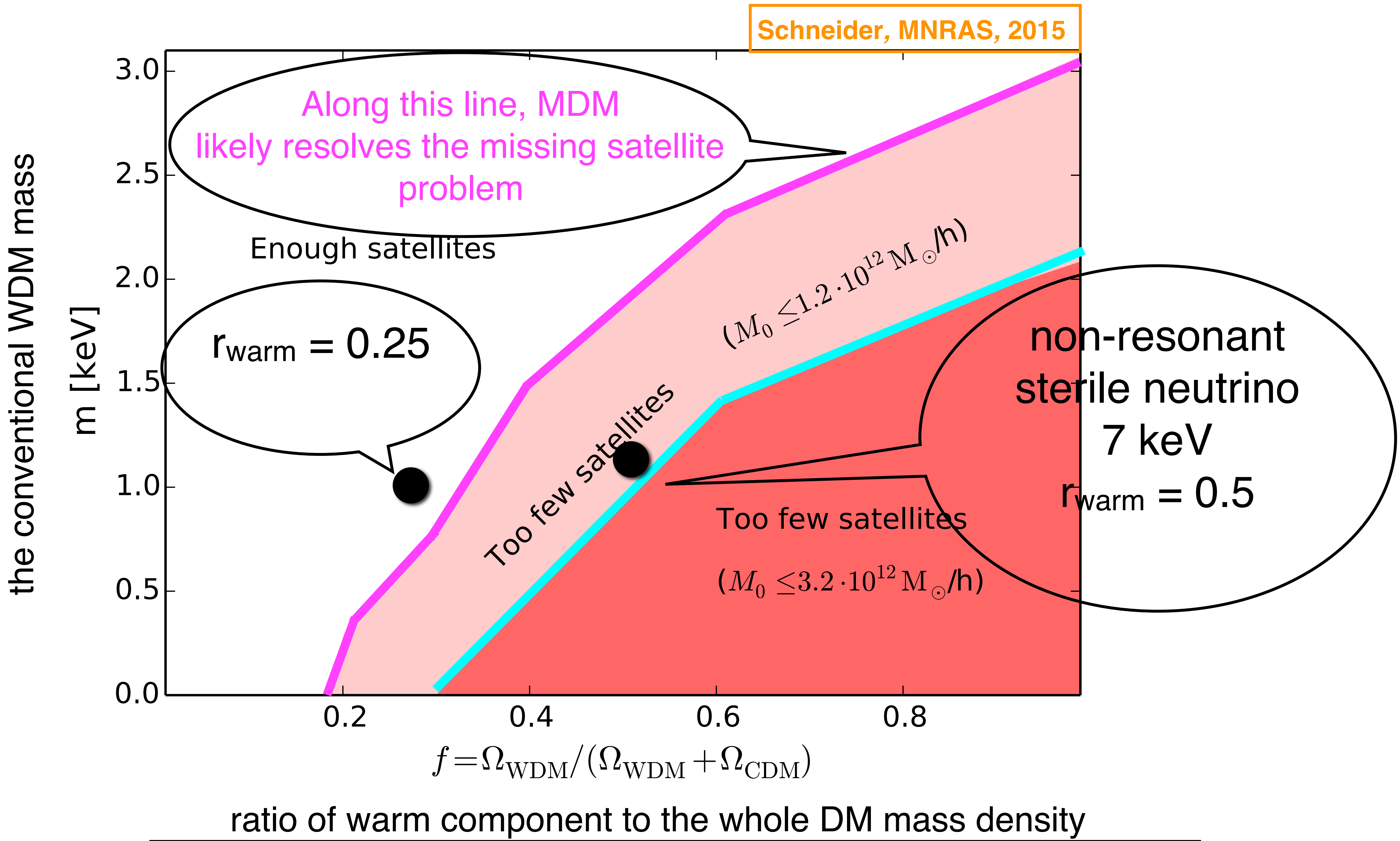


Constraints from Lyman-α forests (MDM)



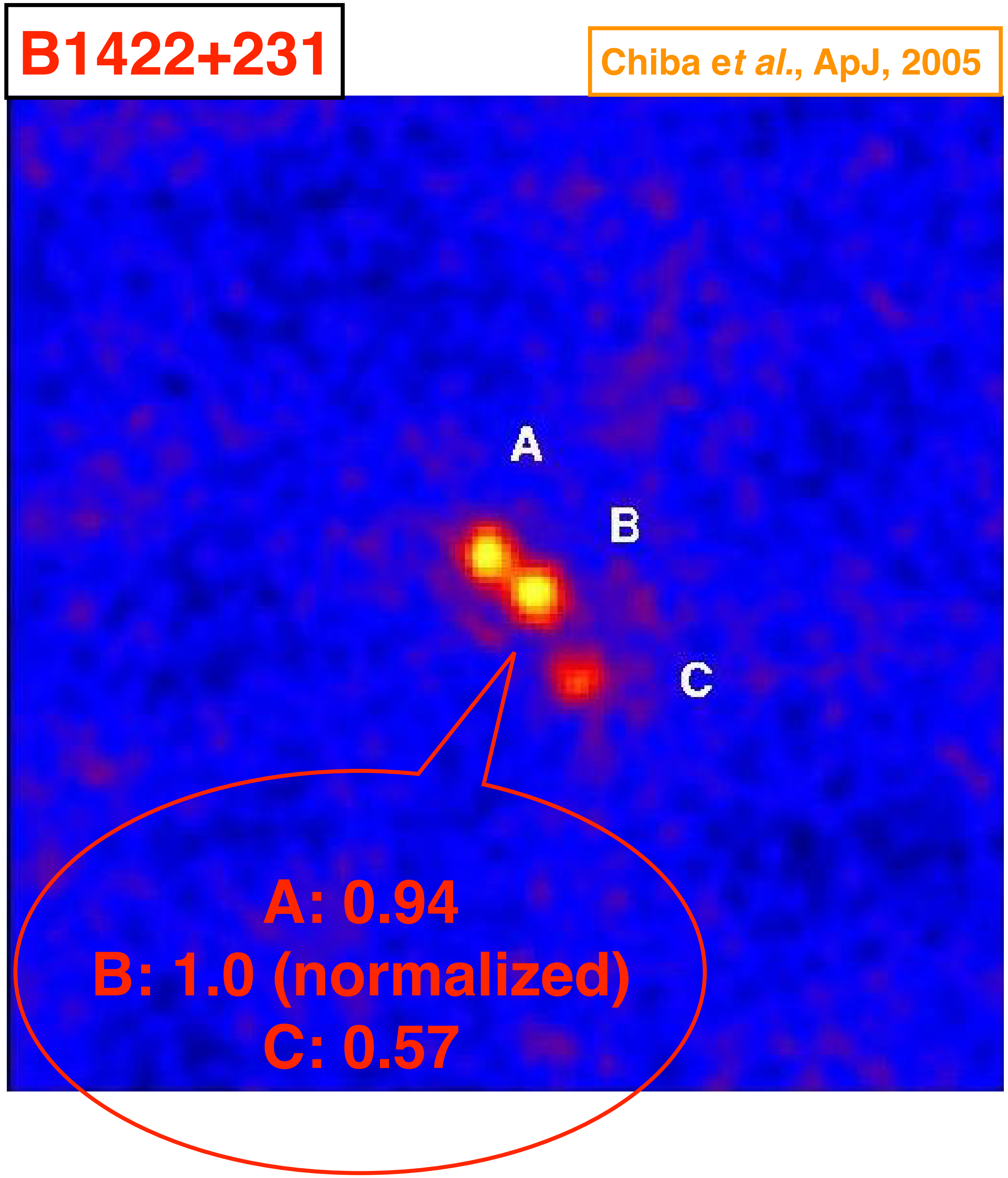
7 keV sterile neutrino WDM may be excluded with 95%CL
MDM with **50%/25%** 7 keV sterile neutrino is allowed within **95%/68%CL**

missing satellite problem in MDM models



Let us take two benchmark lines corresponding to smaller and larger MW masses

Anomalous flux ratio



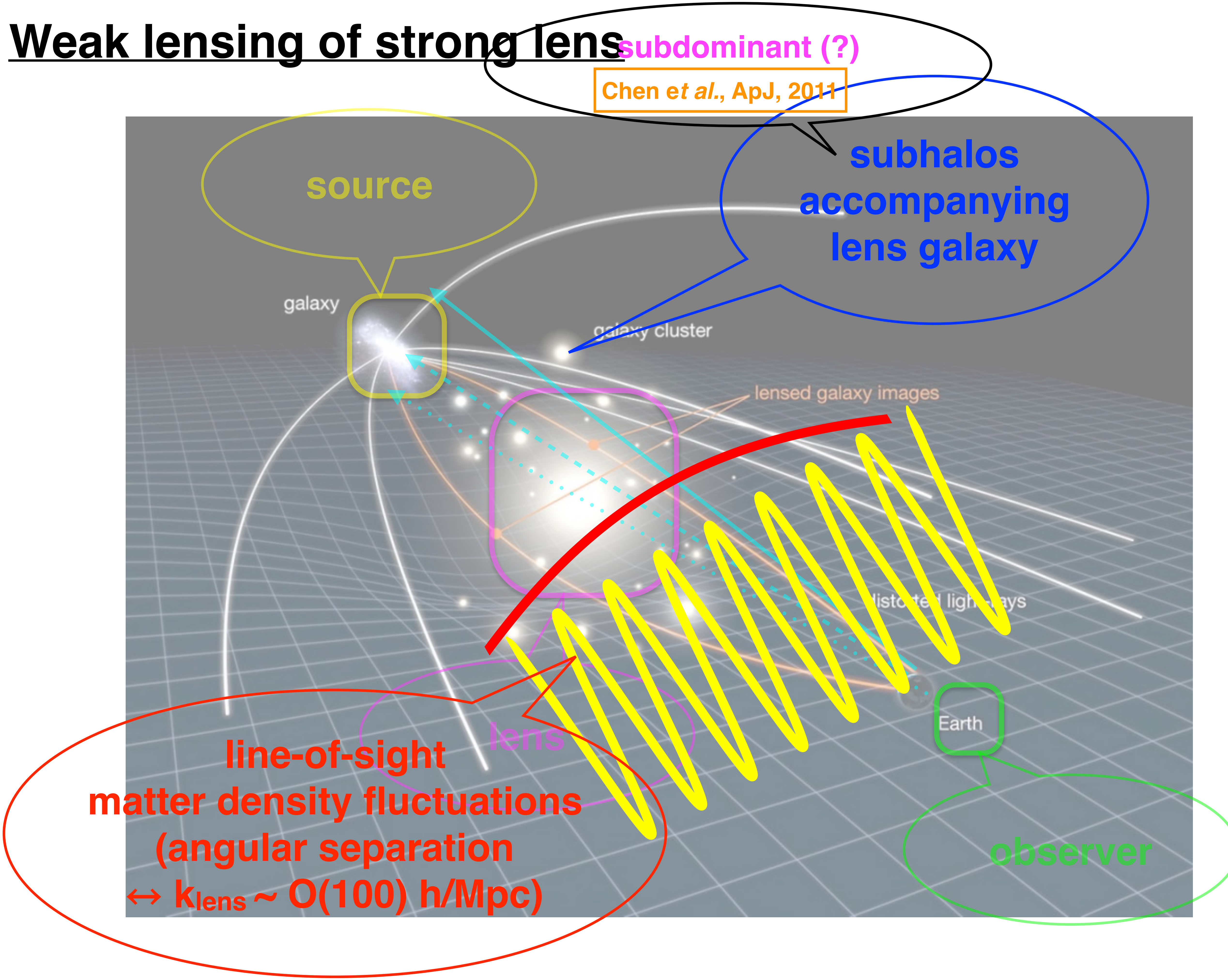
Singular isothermal ellipsoid (SIE) for lens galaxy provides a good-fit for **RELATIVE POSITIONS OF LENSED IMAGES**

1st derivative of gravitational potential

2nd derivative of gravitational potential

Derived FLUX RATIO (A+C)/B =1 is **NOT CONSISTENT WITH** observed value (A+C)/B =1.5 (2σ or more)

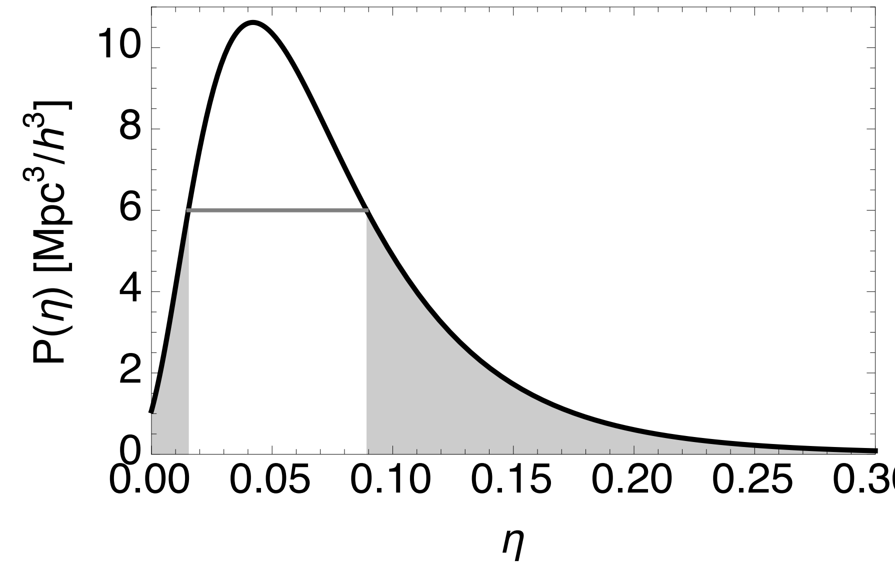
Weak lensing of strong lens

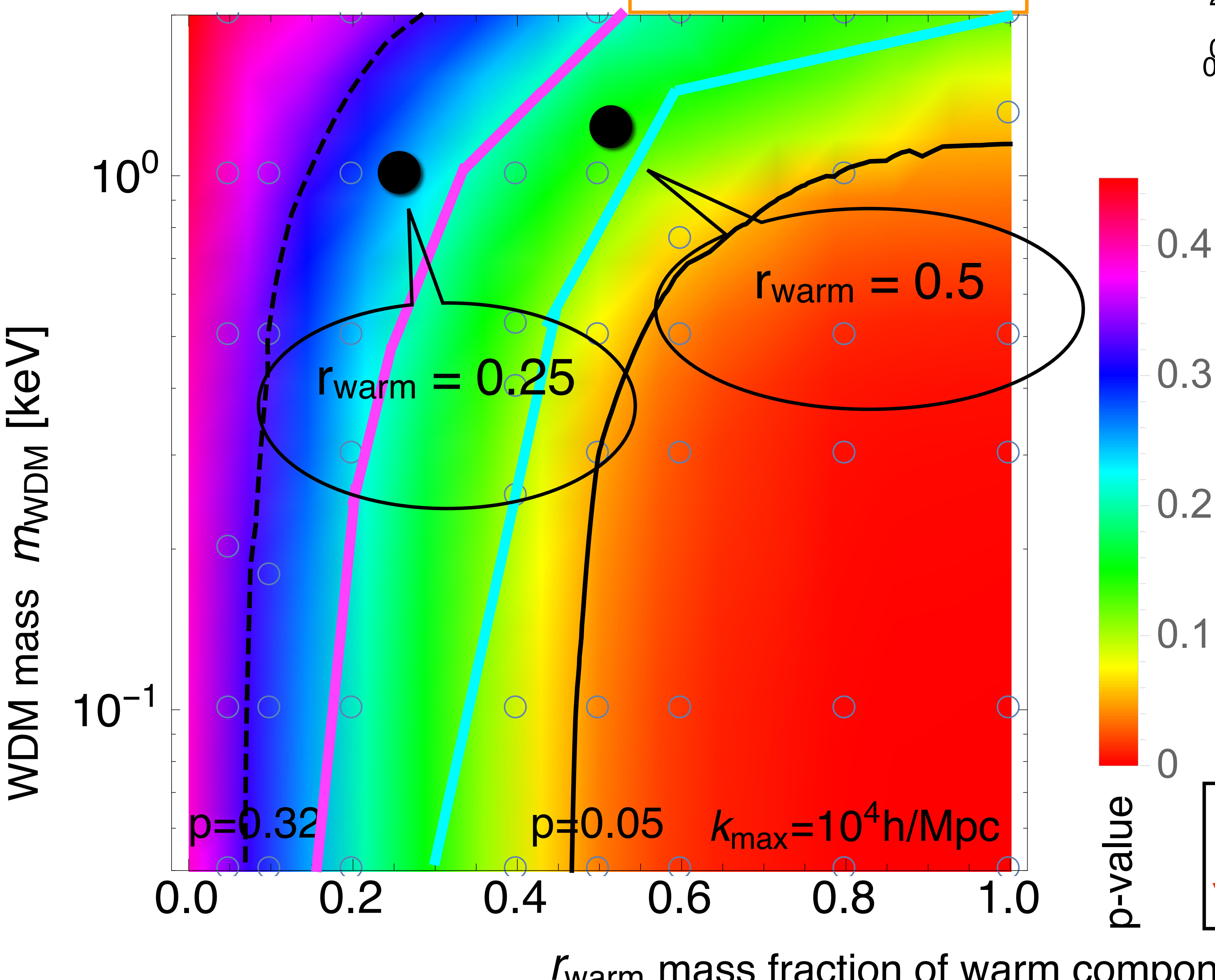


Likelihood

p-value: probability of finding a sample that is more unlikely than the observed value

Kamada et al., PRD, 2016



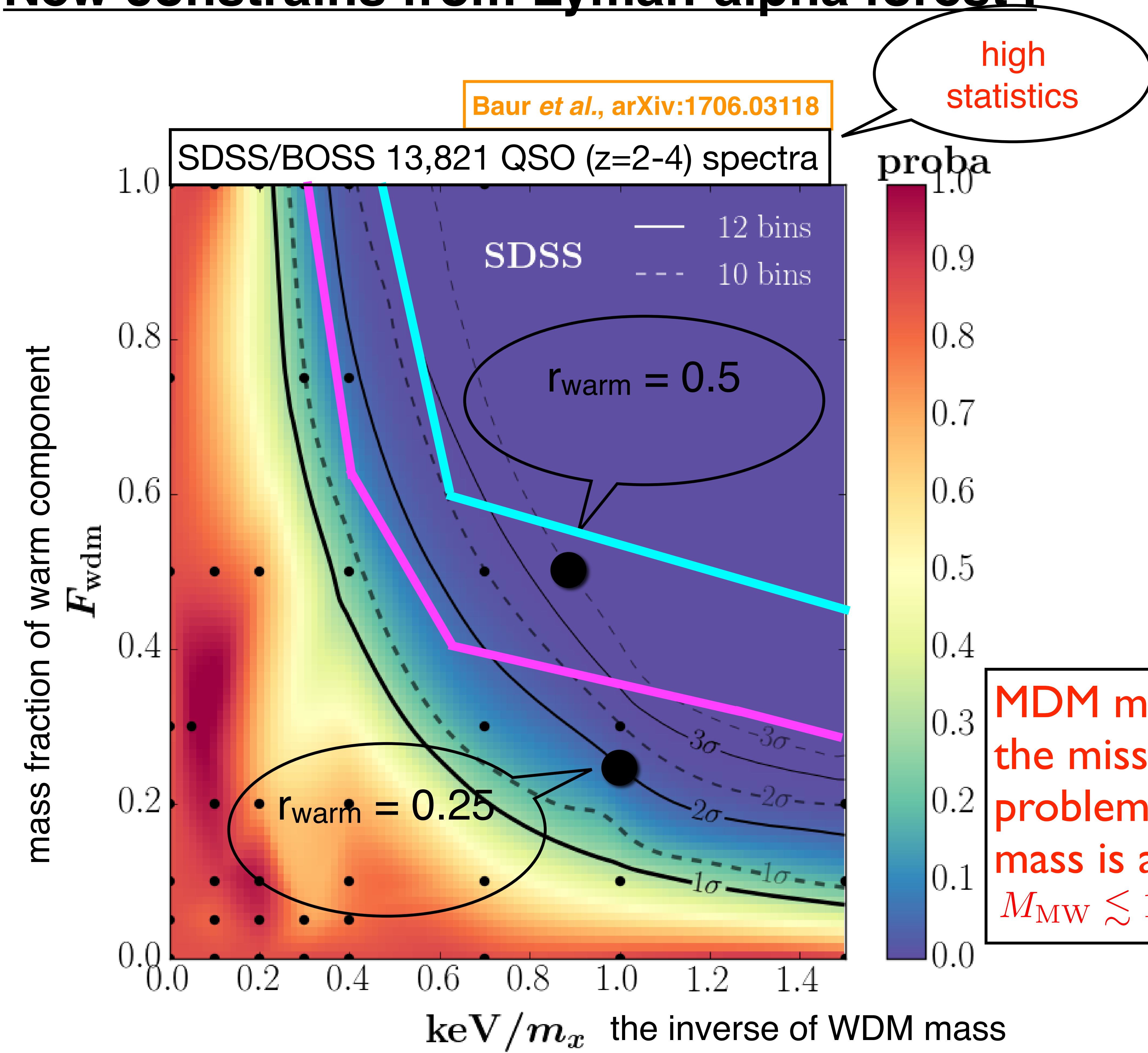


conversion ($r_{\rm warm}$, k_J fixed):

$$m_{\rm WDM} = 1.0\,{\rm keV} \times \left(\frac{m_s}{7\,{\rm keV}}\right)\left(\frac{r_{\rm warm}}{0.25}\right)^{1/4}$$

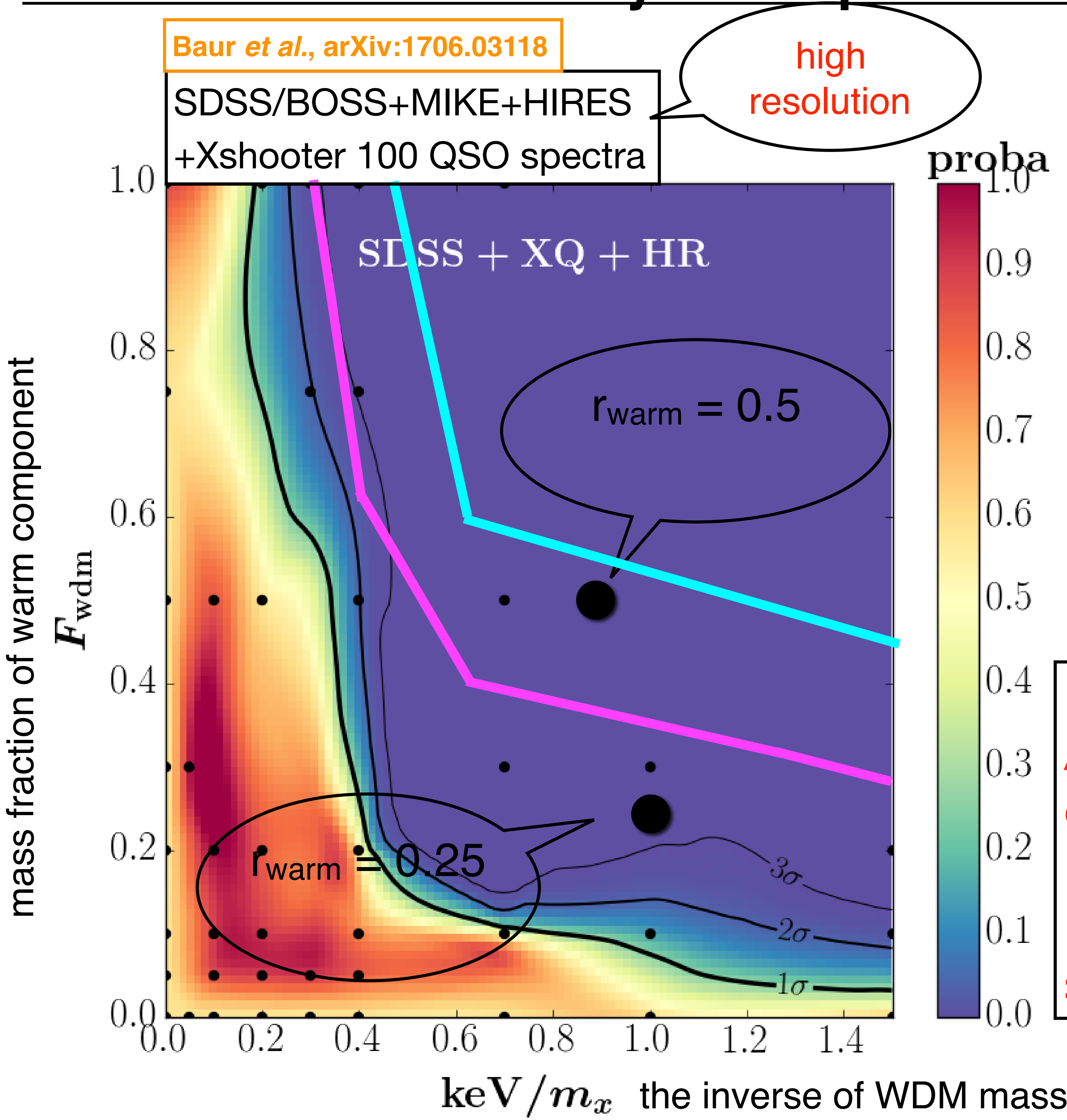
MDM bench marks are viable (within 2σ)

New constrains from Lyman-alpha forest I



MDM may resolve the missing satellite problem if the MW mass is as small as $M_{\rm MW} \lesssim 1.2 \times 10^{12} M_\odot$

New constrains from Lyman-alpha forest II



MDM is likely NOT ABLE TO simultaneously explain the observed Lyman-alpha forest and resolve the missing satellite problem (2σ)

Phase space distribution

Phase space distribution is important for the warmness:

$$m = 7\,\mathrm{keV}\left(\frac{m_{\mathrm{WDM}}}{2.5\,\mathrm{keV}(\tilde{\sigma}/3.6)^{-3/4}}\right)^{4/3}, \quad \tilde{\sigma}^2 = \frac{\int dq q^4 f(q)}{\int dq q^2 f(q)}$$

Boltzmann equation:

Hubble expansion

collision term

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

FIMP → $f_{\tilde{a}} \ll 1$ can be ignored in the collision term

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

sum over all the processes

Benchmark points

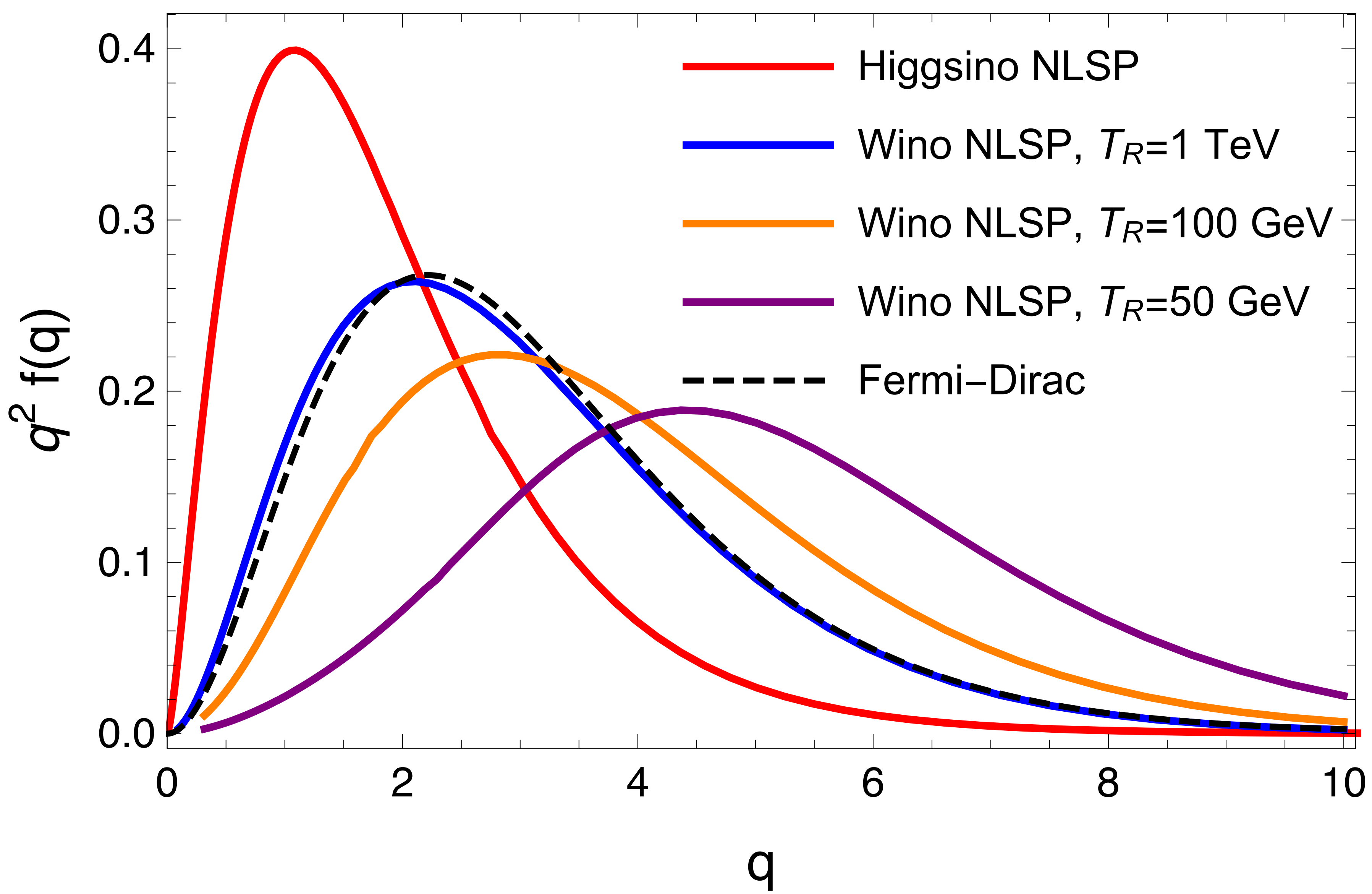
$f_{\tilde{a}}$ is a sum of all the contributions
freeze-in → the next-to-the-lightest supersymmetric particle (NLSP) provides a dominant contribution
BM1: Higgsino NLSP
BM2: wino NLSP

		BM1	BM2
Higgs VEV ratio	$\tan\beta$	20	20
μ-term	μ	500 GeV	10 TeV
wino mass	M_2	10 TeV	500 GeV
CP-odd Higgs mass	m_A	10 TeV	20 TeV
stop masses	$m_{\widetilde{Q}_3} = m_{\tilde{t}^c}$	6.5 TeV	10 TeV
SM-like Higgs mass	$m_h^{\mathrm{SM-like}}$	125 GeV	126 GeV
H_u soft mass	$m^2_{H_u}(Q = m_{\tilde{t}^c})$	$(956\,\mathrm{GeV})^2$	$-(9.86\,\mathrm{TeV})^2$
H_d soft mass	$m^2_{H_d}(Q = m_{\tilde{t}^c})$	$(9.94\,\mathrm{TeV})^2$	$(17.3\,\mathrm{TeV})^2$

TABLE II: MSSM parameters of BM1 and BM2 are shown. The SM-like Higgs mass and soft masses at $Q = m_{\tilde{t}^c}$ are calculated by `SUSY-HIT v1.5a` [88]. The masses of the other SUSY particles are taken to be 10 TeV.

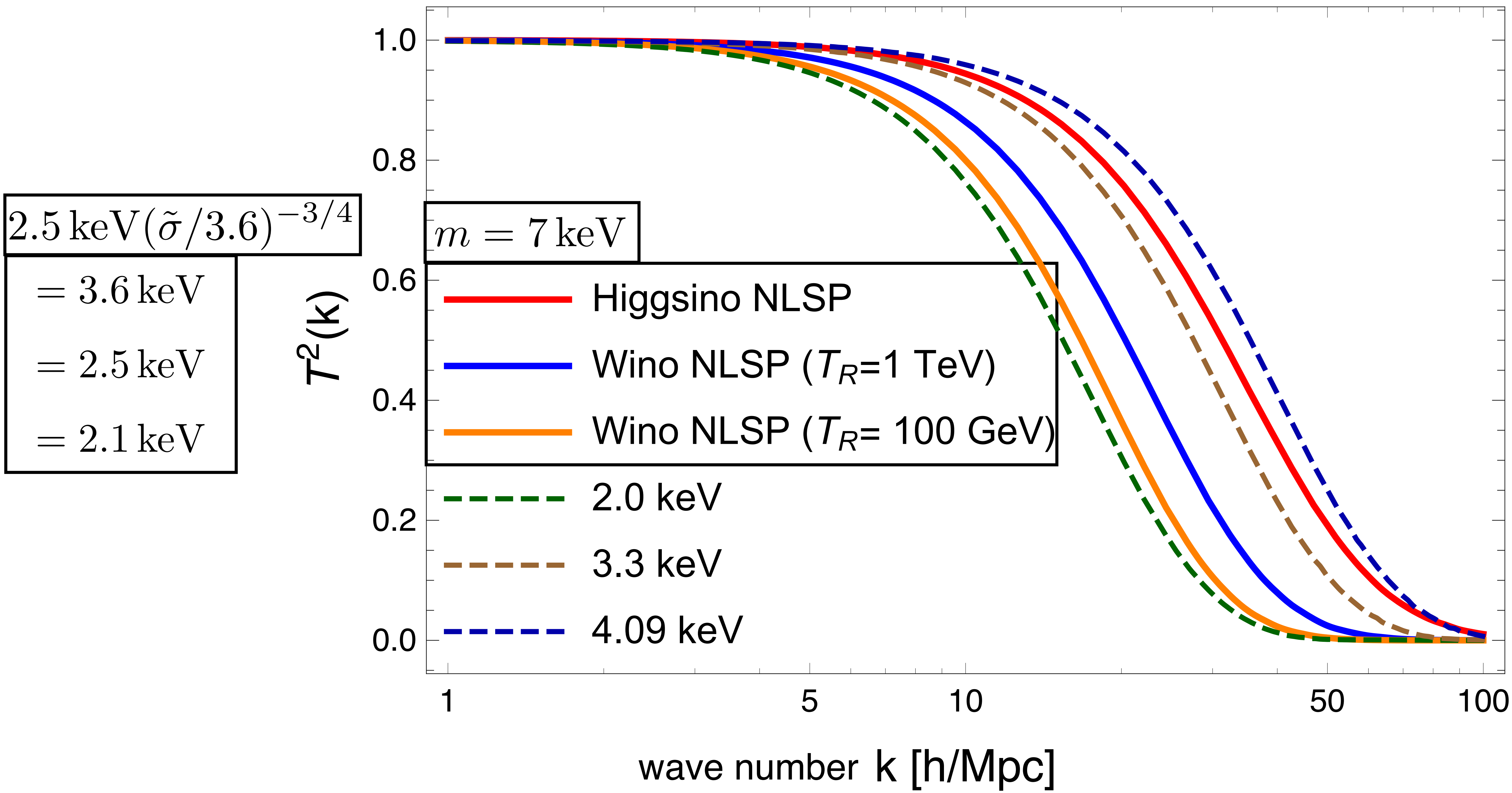
Phase space distributions in the BM points

phase space distribution from each process
normalized so that $\int dq\, q^2 f(q) = 1$, $p = T_{\tilde{a}} q$, $T_{\tilde{a}} = \left(\frac{g_*(T)}{g_*(T_{\rm dec})} \right)^{1/3} T$



BM1, where Higgs 2-body decay is dominant, results in the coldest phase space distribution

Linear matter power spectrum in the BM points



$$m = 7\,\mathrm{keV}\left(\frac{m_{\mathrm{WDM}}}{2.5\,\mathrm{keV}(\tilde{\sigma}/3.6)^{-3/4}}\right)^{4/3}$$

most stringent bound:

$m_{\mathrm{WDM}} > 5.3\,\mathrm{keV}$

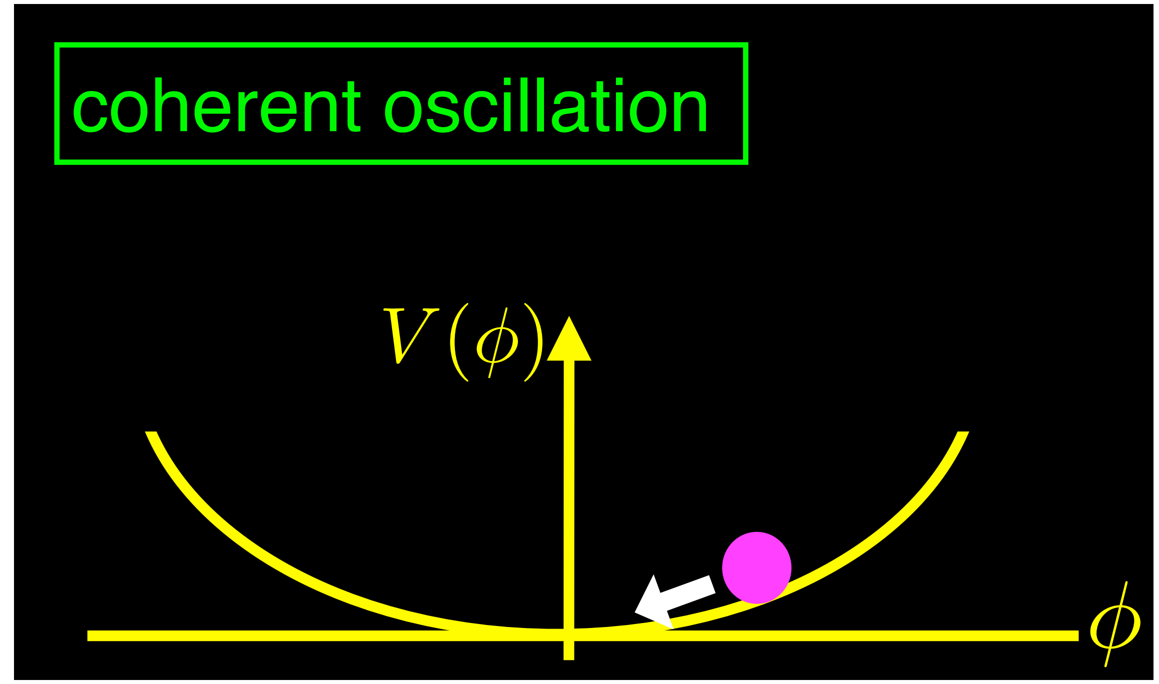
Entropy production from the saxion decay

Even the coldest phase space distribution (BM1) does not satisfy $m_{\mathrm{WDM}} > 5.3\,\mathrm{keV}$

saxion coherent oscillation:

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

$$3\frac{\dot{R}}{R}\bigg|_{T=T_s} = m_s$$



saxion domination (T_e^s)and decay (T_D^s) → entropy production

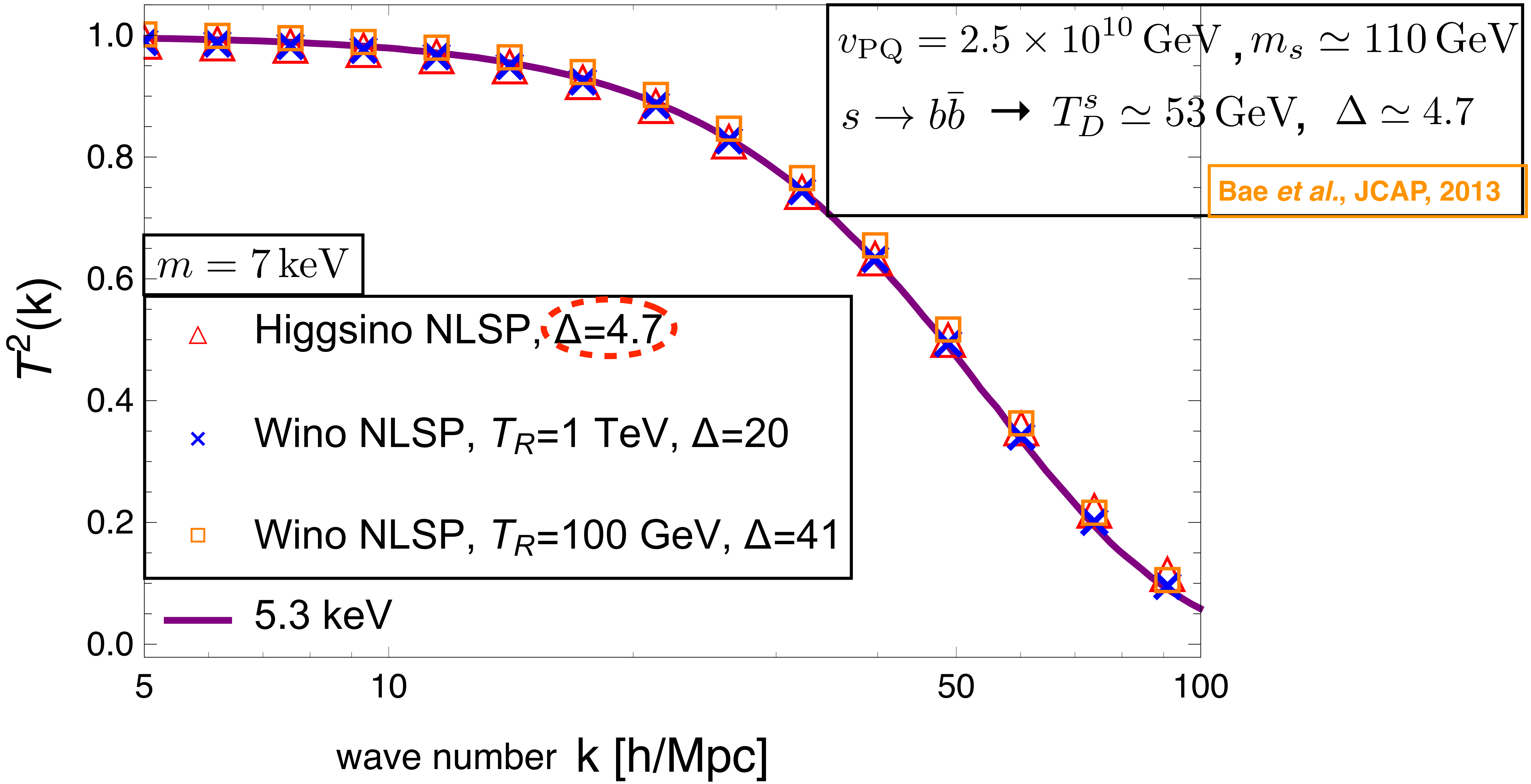
$$\Delta = \frac{s_{\mathrm{w}}}{s_{\mathrm{wo}}} \simeq \frac{T_e^s}{T_D^s}\,, \quad T_e^s = \frac{4}{3} m_s Y_s^{\mathrm{CO}} \simeq 2.5 \times 10^2\,\mathrm{GeV} \left(\frac{\min[T_R, T_s]}{10^7\,\mathrm{GeV}}\right) \left(\frac{s_0}{10^{16}\,\mathrm{GeV}}\right)^2$$

saxion domination after the freeze-in $T_e^s \ll \mu, M_2$ → colder axino

$$T_{\tilde{a}} = \left(\frac{g_*(T)}{g_*(T_{\mathrm{dec}})}\right)^{1/3} T \quad \Rightarrow \quad T_{\tilde{a}} = \left(\frac{g_*(T)}{\Delta\, g_*(T_{\mathrm{th}})}\right)^{1/3} T$$

Linear matter power spectrum w/ entropy production

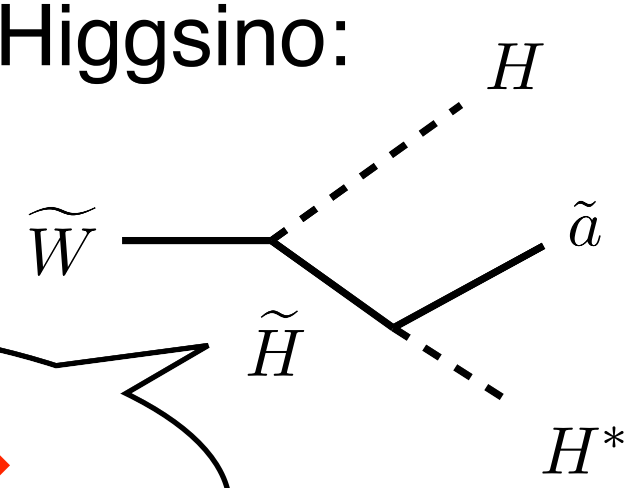
$$m = 7\,\mathrm{keV}\left(\frac{m_{\rm WDM}}{2.5\,\mathrm{keV}(\tilde{\sigma}/3.6)^{-3/4}}\right)^{4/3} \Rightarrow \left(\frac{m_{\rm WDM}}{2.5\,\mathrm{keV}\Delta^{1/4}(\tilde{\sigma}/3.6)^{-3/4}}\right)^{4/3}$$



Caveats on 3-body decay

3-body decay of wino through heavier Higgsino:

freeze-in at $T \sim M_2$

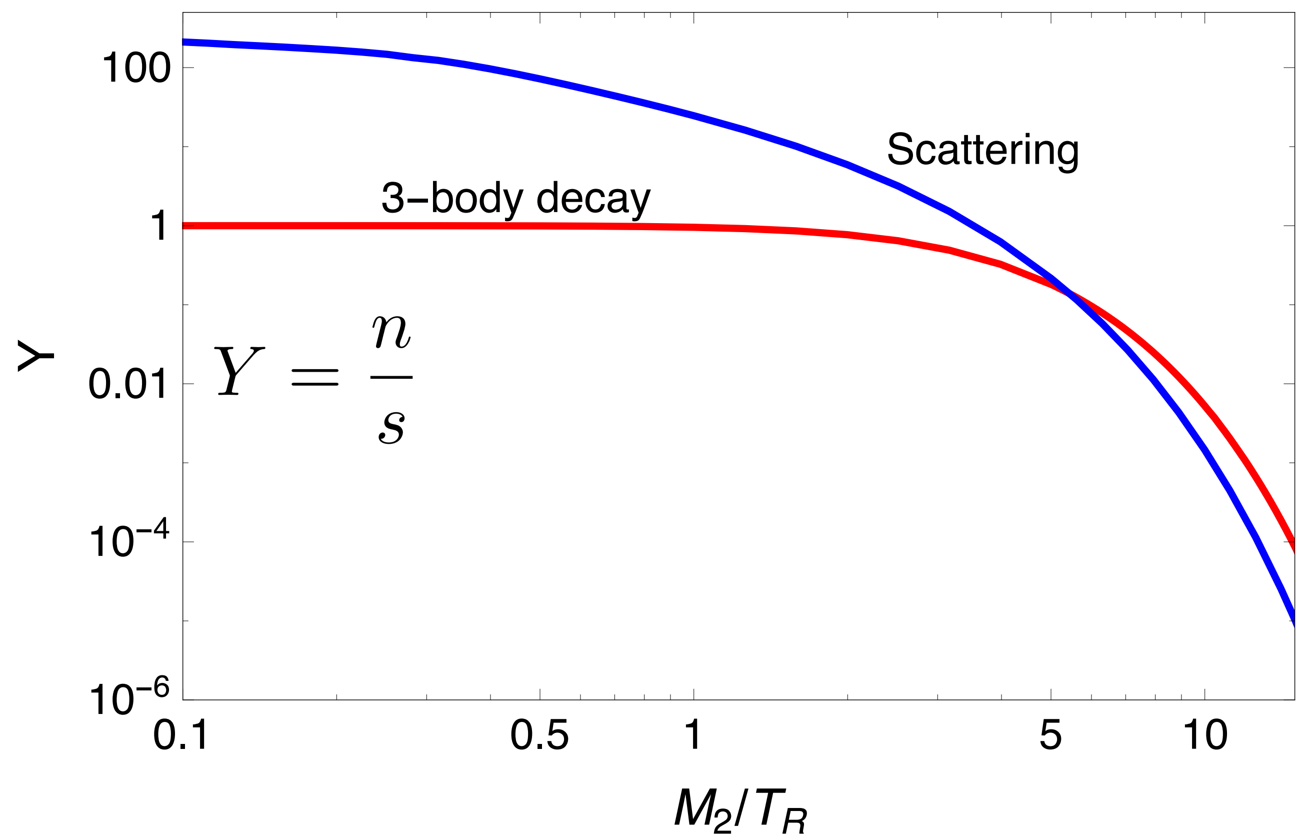


Heavy particle →
dimension 5 operator

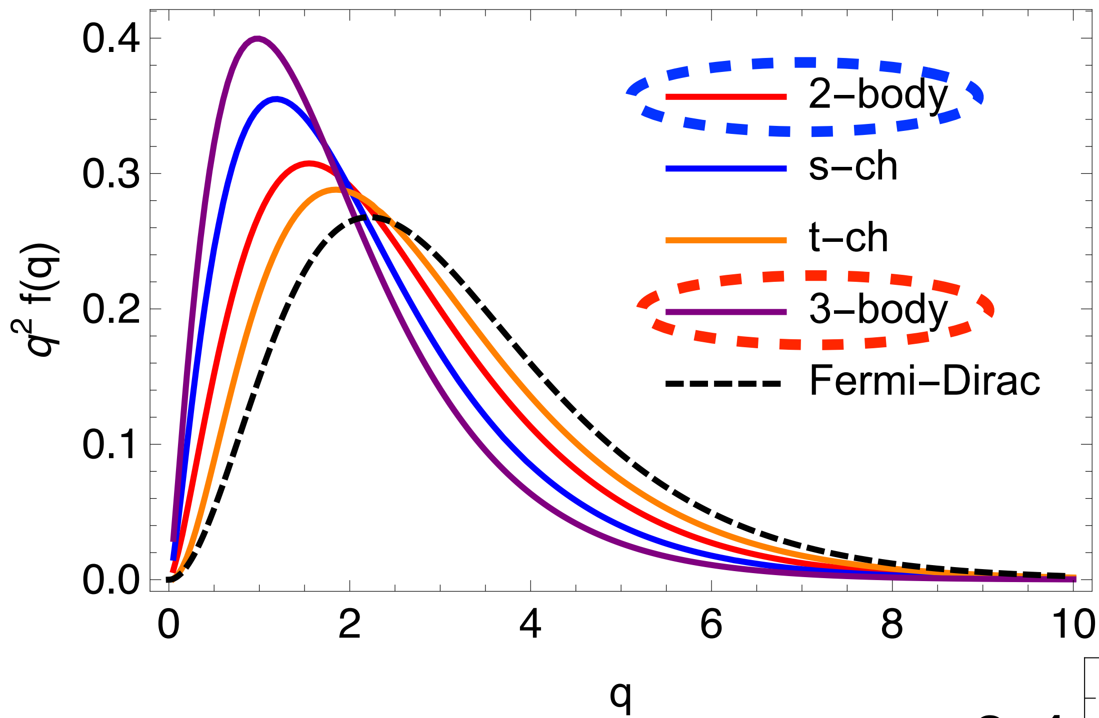
Scatterings at $T = T_R < \mu$ are more efficient

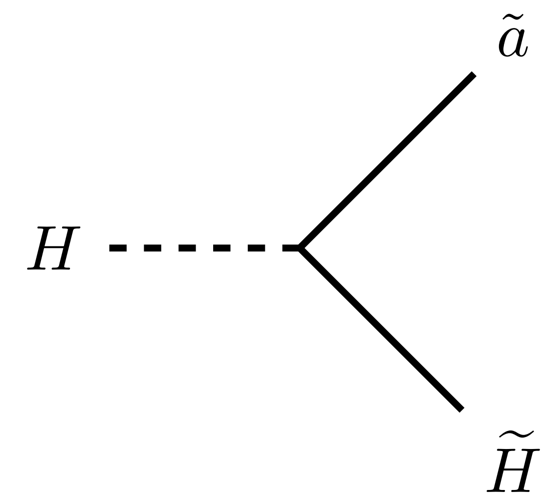
3-body decay is dominant
when $T_R < M_2/5$
↔ the phase space

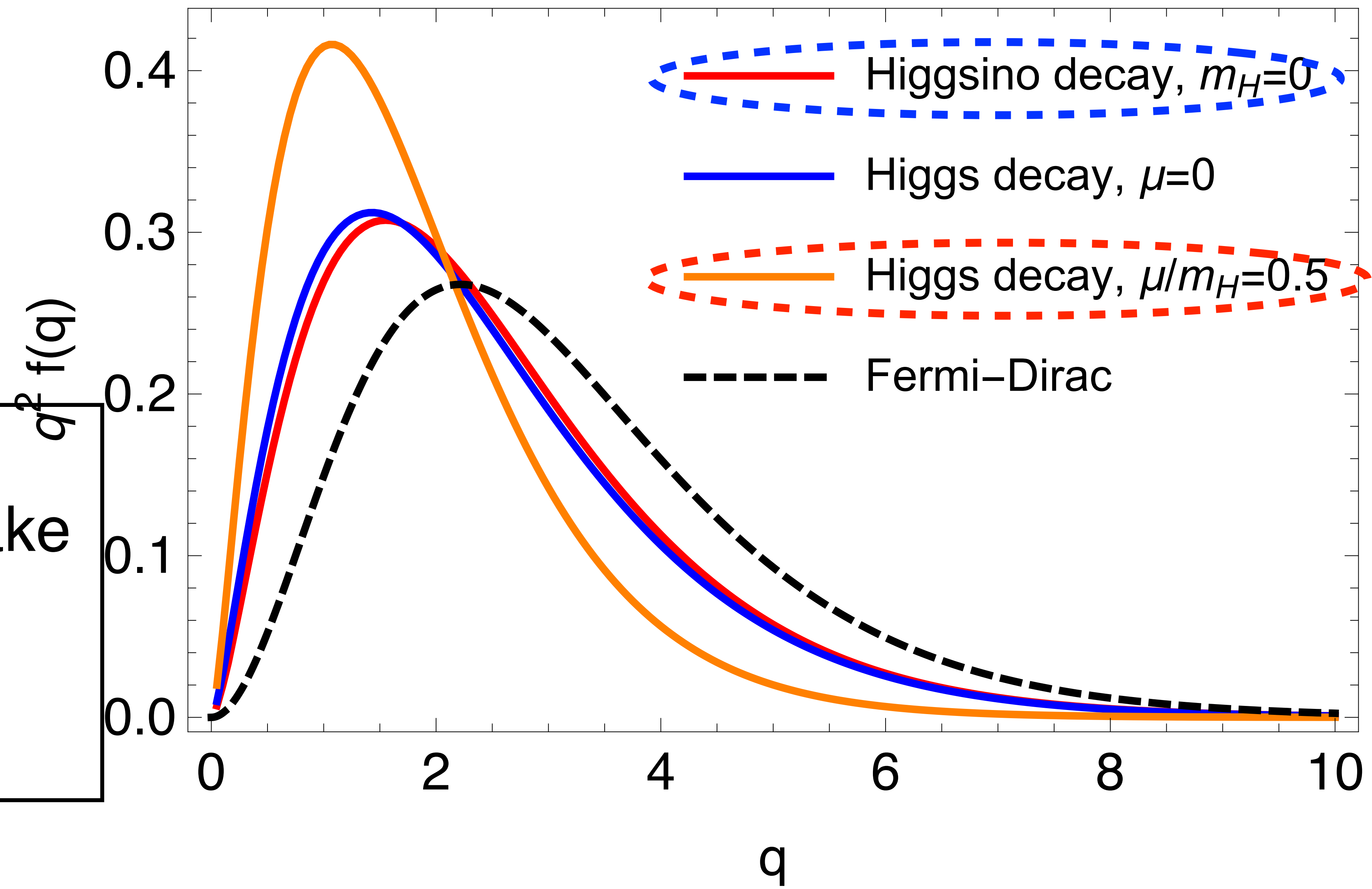
distribution is hotter



Effects of a degenerate mass spectrum





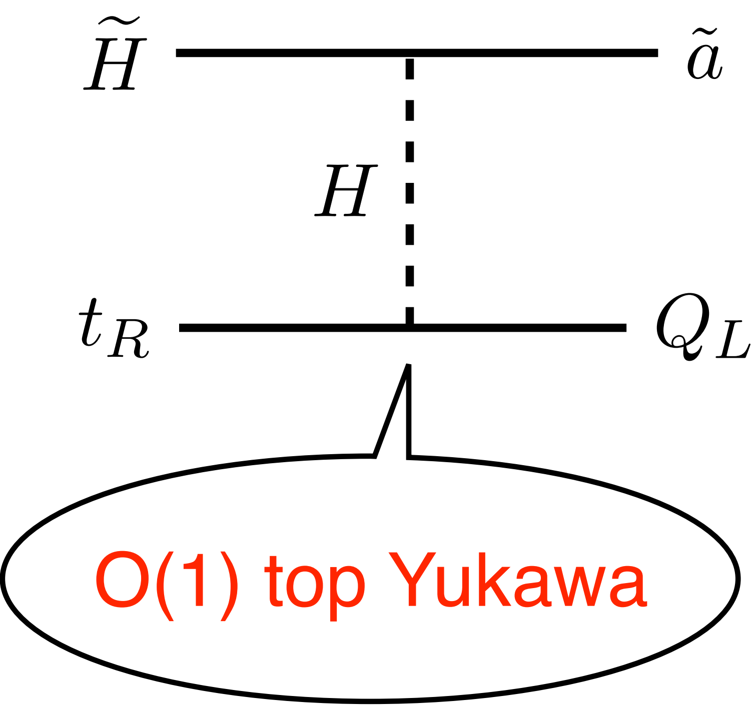


By tuning the mass spectrum, we may make the phase space distribution colder

Heek *et al.*, arXiv: 1706. 09909

Caveats on a degenerate mass spectrum

The mass degeneracy also suppresses the decay rate
→ scatterings become dominant



$$\boxed{2.5\,\mathrm{keV}(\tilde{\sigma}/3.6)^{-3/4}}$$

$$= 4.2\,\mathrm{keV}$$

$$= 5.3\,\mathrm{keV}$$