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

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Based on
AK, and Keisuke Yanagi, arXiv:1907.04558
see also
Kyu Jung Bae, AK, Seng Pei Liew, and Keisuke Yanagi, JCAP, 2018
Kyu Jung Bae, Ryusuke Jinno, AK, and Keisuke Yanagi, arXiv:1906.09141

Aug. 22, 2019 @ SI2019

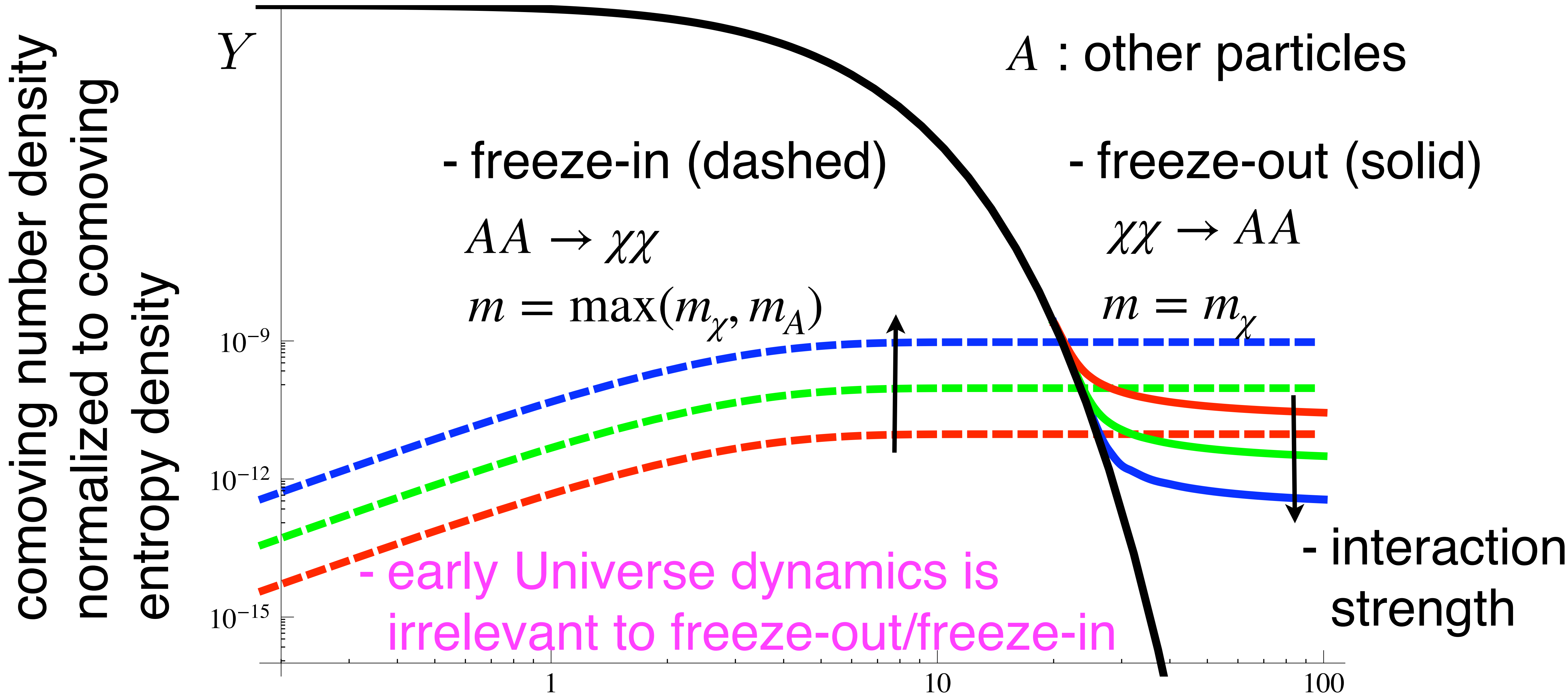
Dark matter thermal production

Tongyan Lin's lecture

Hall, Jedamzik, March-Russell, and West, JHEP, 2010

χ : DM particle

A : other particles



mass normalized to temperature $x = m/T$

Freeze out: Weakly Interacting Massive Particle (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 (WDM)

- alter galactic-scale structure of the Universe

Collider: long-lived particle A

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

We will discuss

Is 7 keV FIMP DM consistent w/ structure formation? part 1

- thermal WDM $m_{\rm WDM}$ is often taken as a fiducial model
- constraints on $m_{\rm WDM}$ are not directly applicable to FIMPs

Constraining FIMPs from structure formation? part 2

- direct procedure is multidisciplinary and time-consuming
- mapping from $m_{\rm WDM}$ via warmness σ^2
- analytic mapping in a benchmark setup

Part 1: Fiducial model of WDM

Thermal WDM: early decoupled fermion like SM neutrino

- WDM particles 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

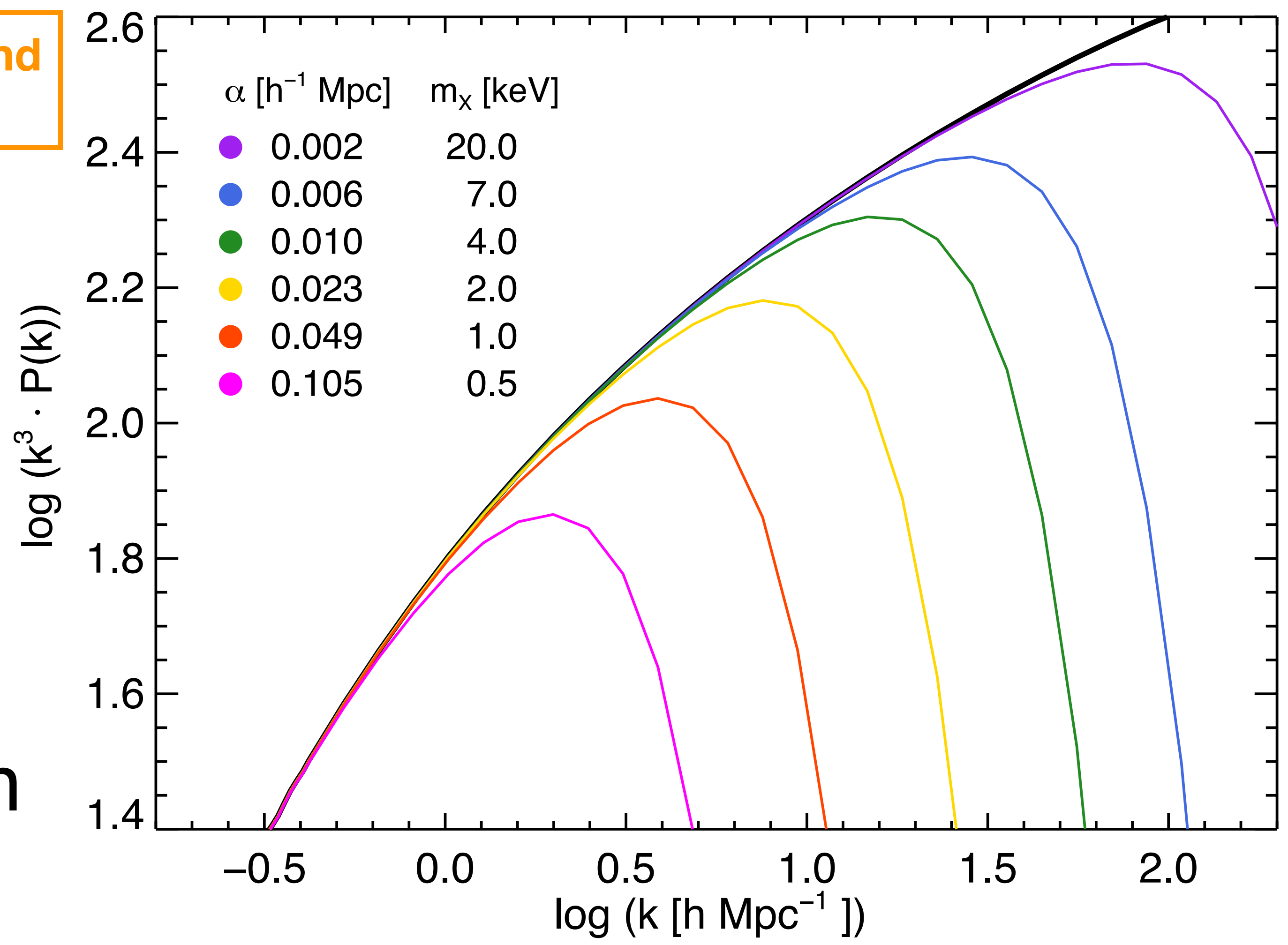
m_{WDM} parametrizes the linear matter power spectrum:

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

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

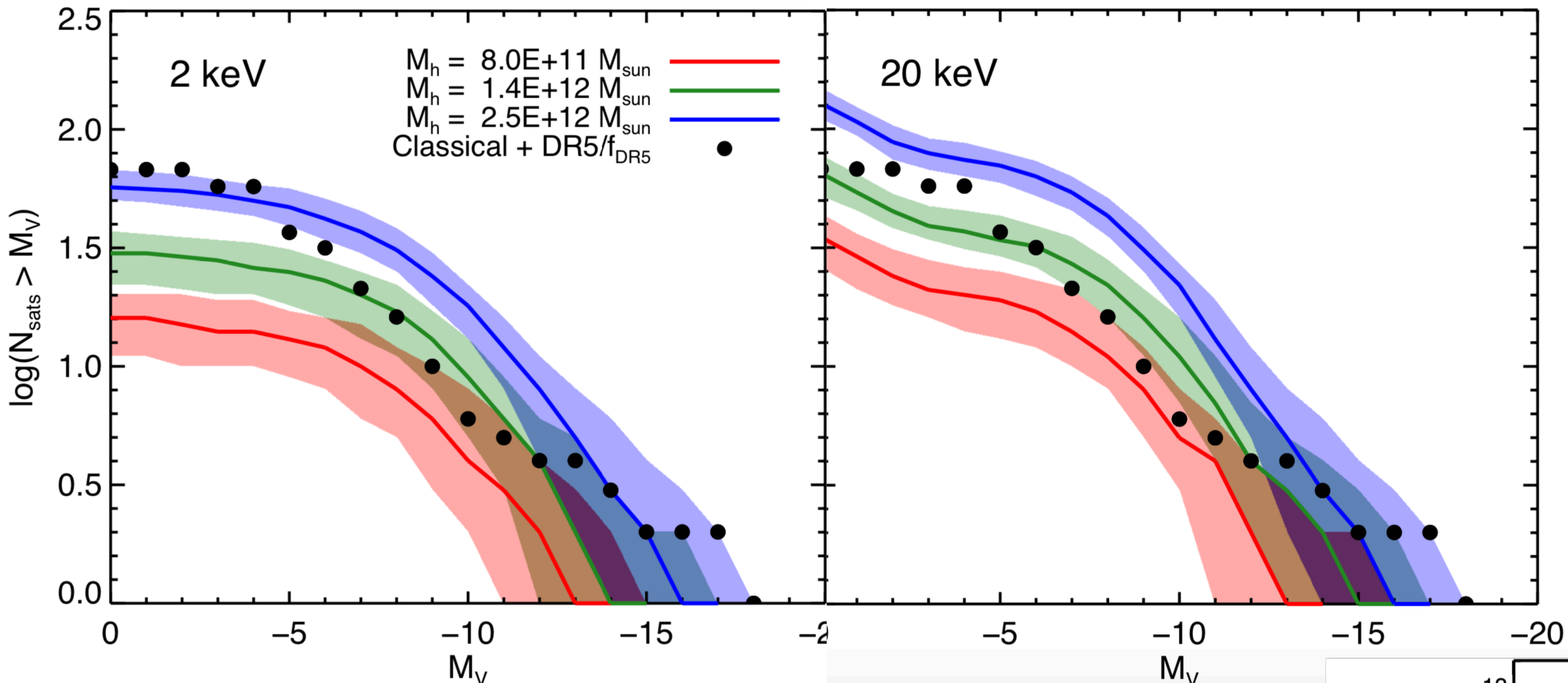
$$\alpha = 0.049\,\mathrm{Mpc}/h \left(\frac{m_{\mathrm{WDM}}}{\mathrm{keV}}\right)^{-1.11} \left(\frac{\Omega_{\mathrm{WDM}}}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22}$$

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



WDM provides less seed for small-scale structure formation

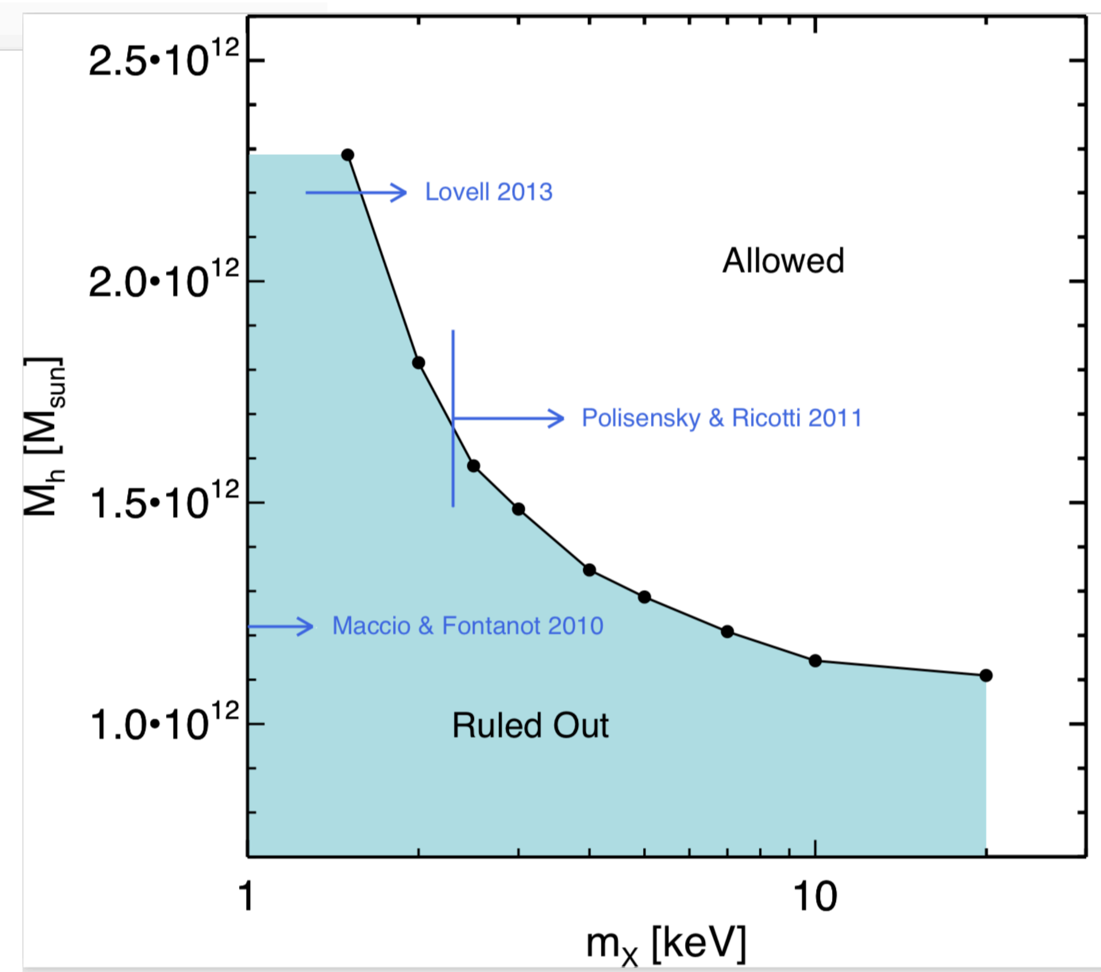
Missing satellite problem w/ WDM



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

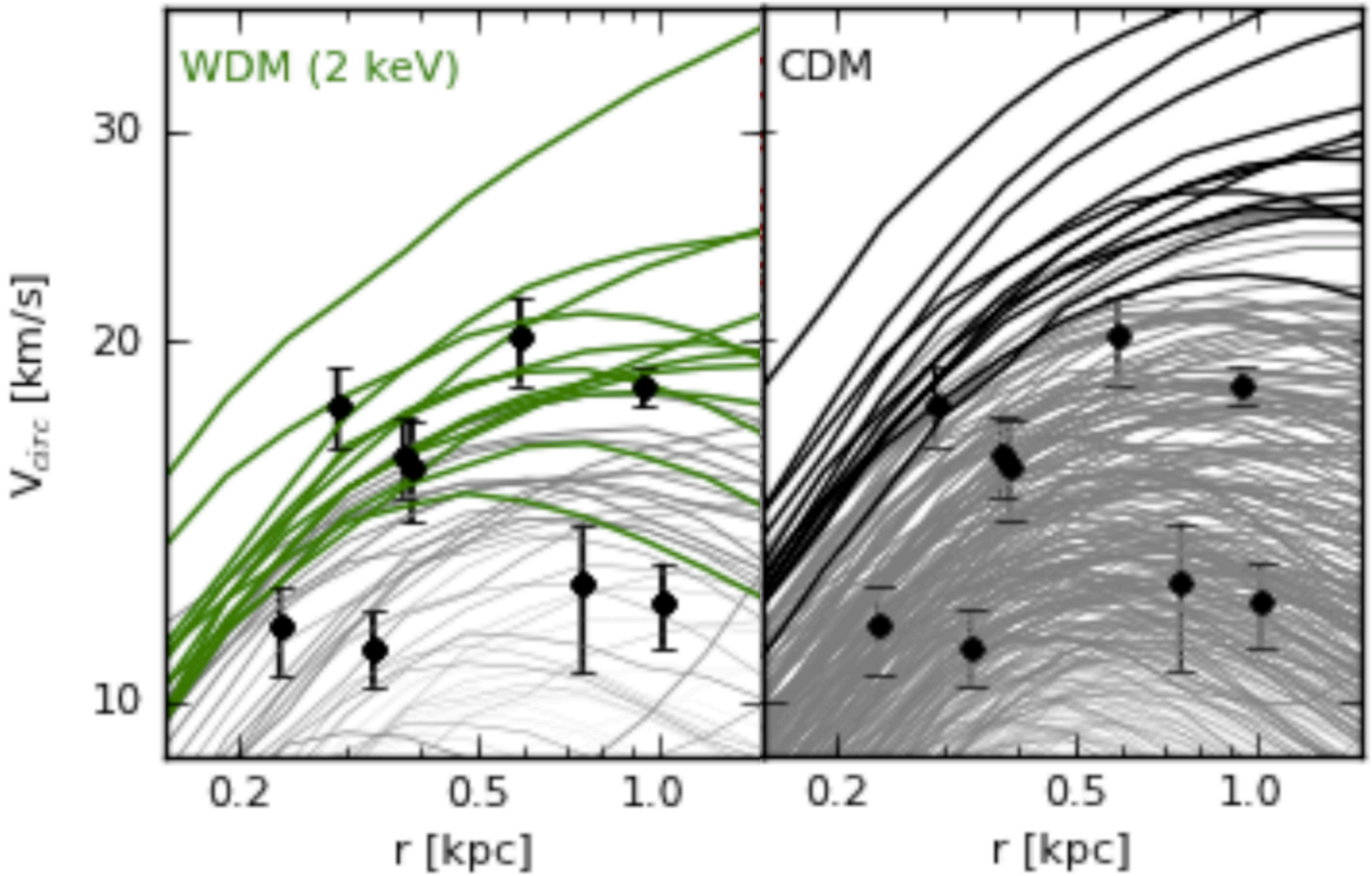
WDM reduces a predicted number of satellite galaxies

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



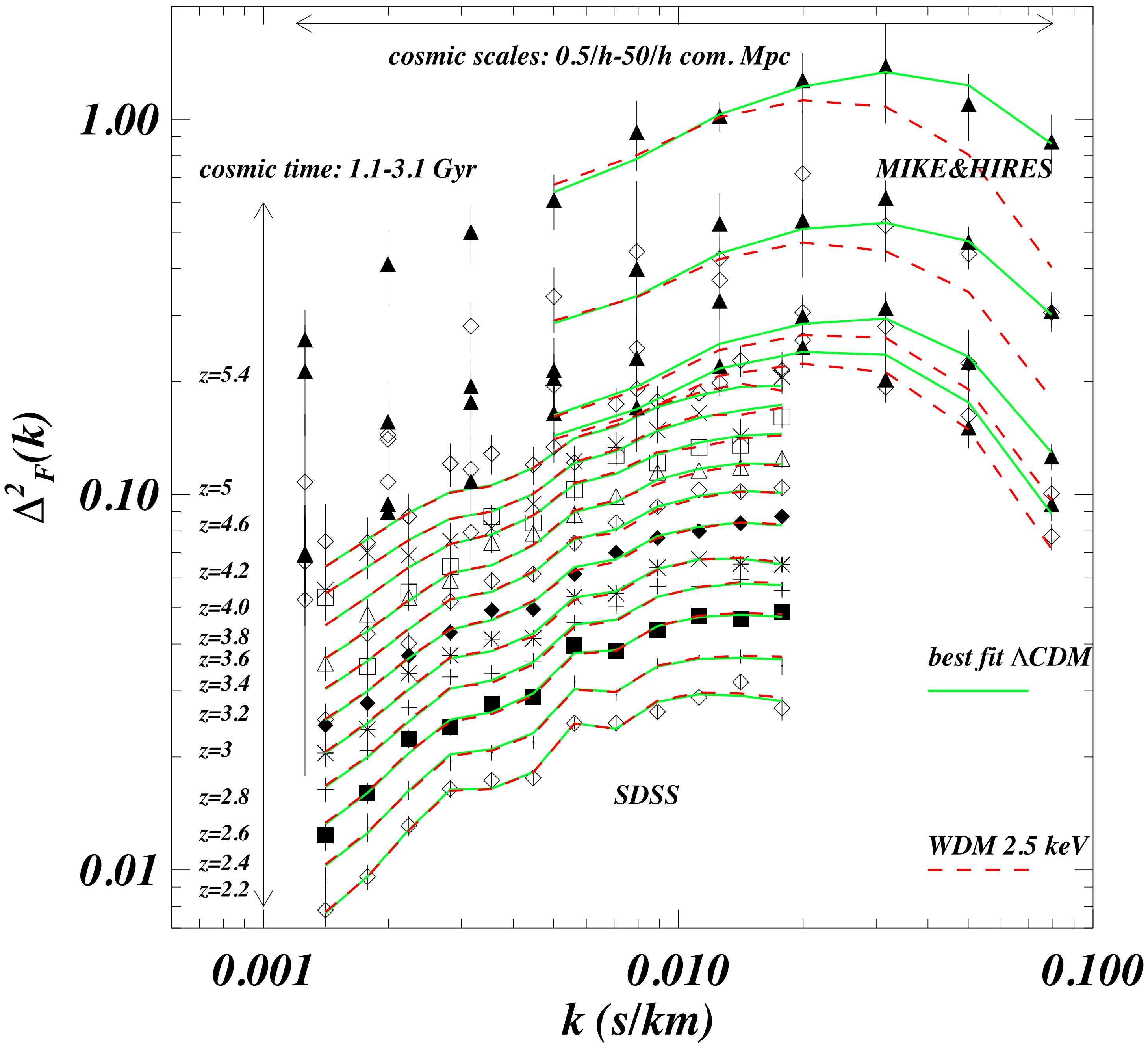
Too-big-to-fail problem w/ WDM

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



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

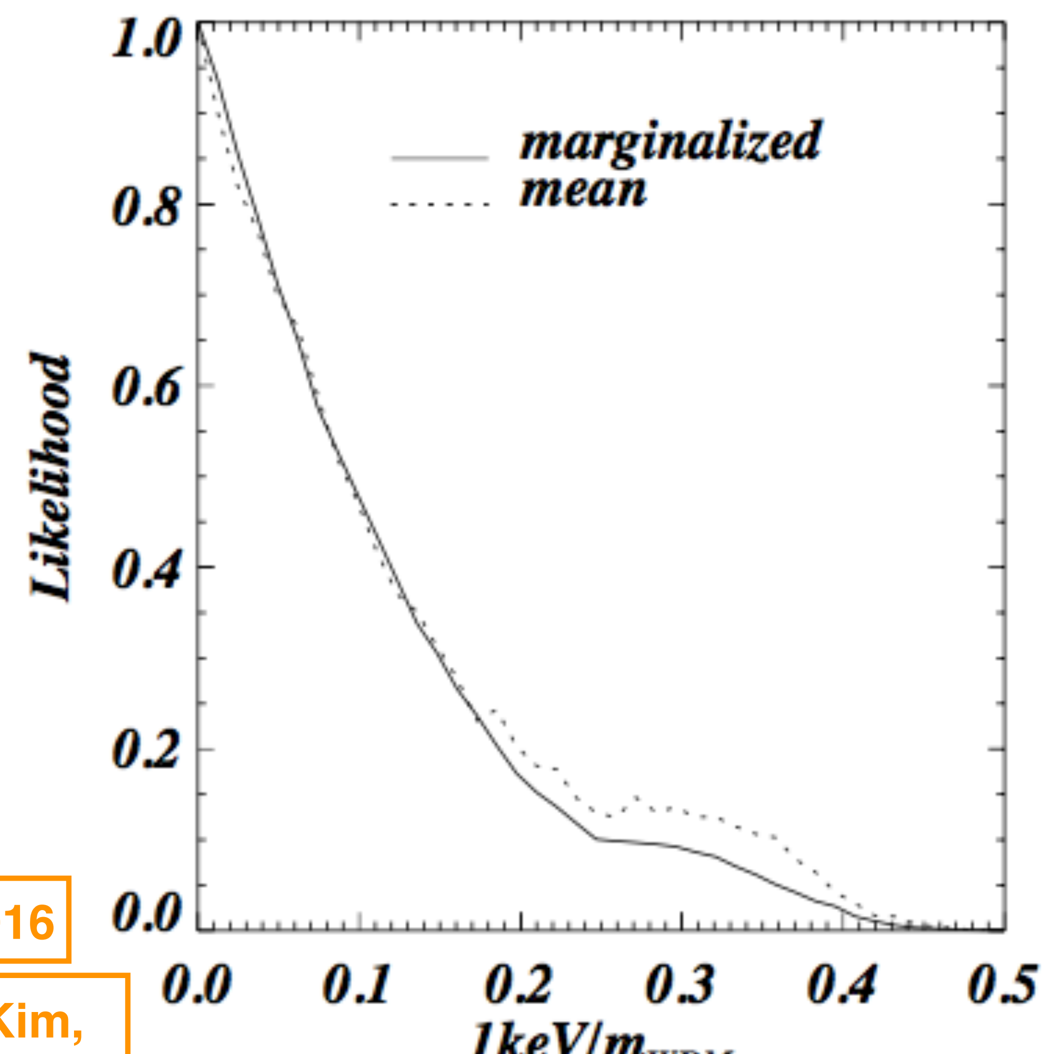
Lyman-α forest constraints on WDM



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

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

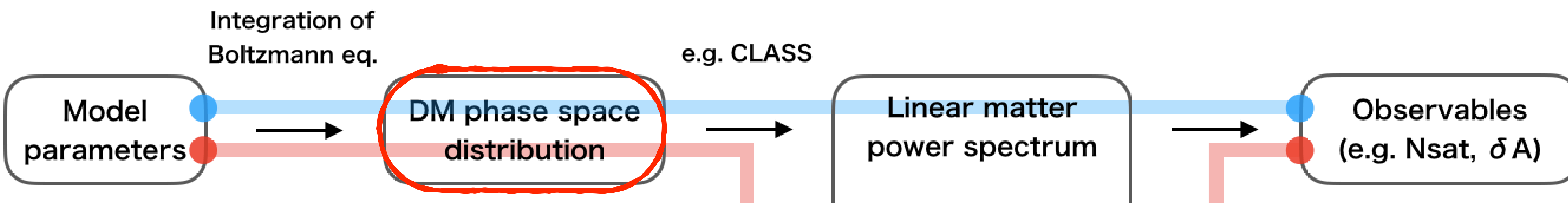
$$T_{\rm DM} = \left(\frac{g_*(T)}{g_*(T_{\rm dec})}\right)^{1/3} T$$

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

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

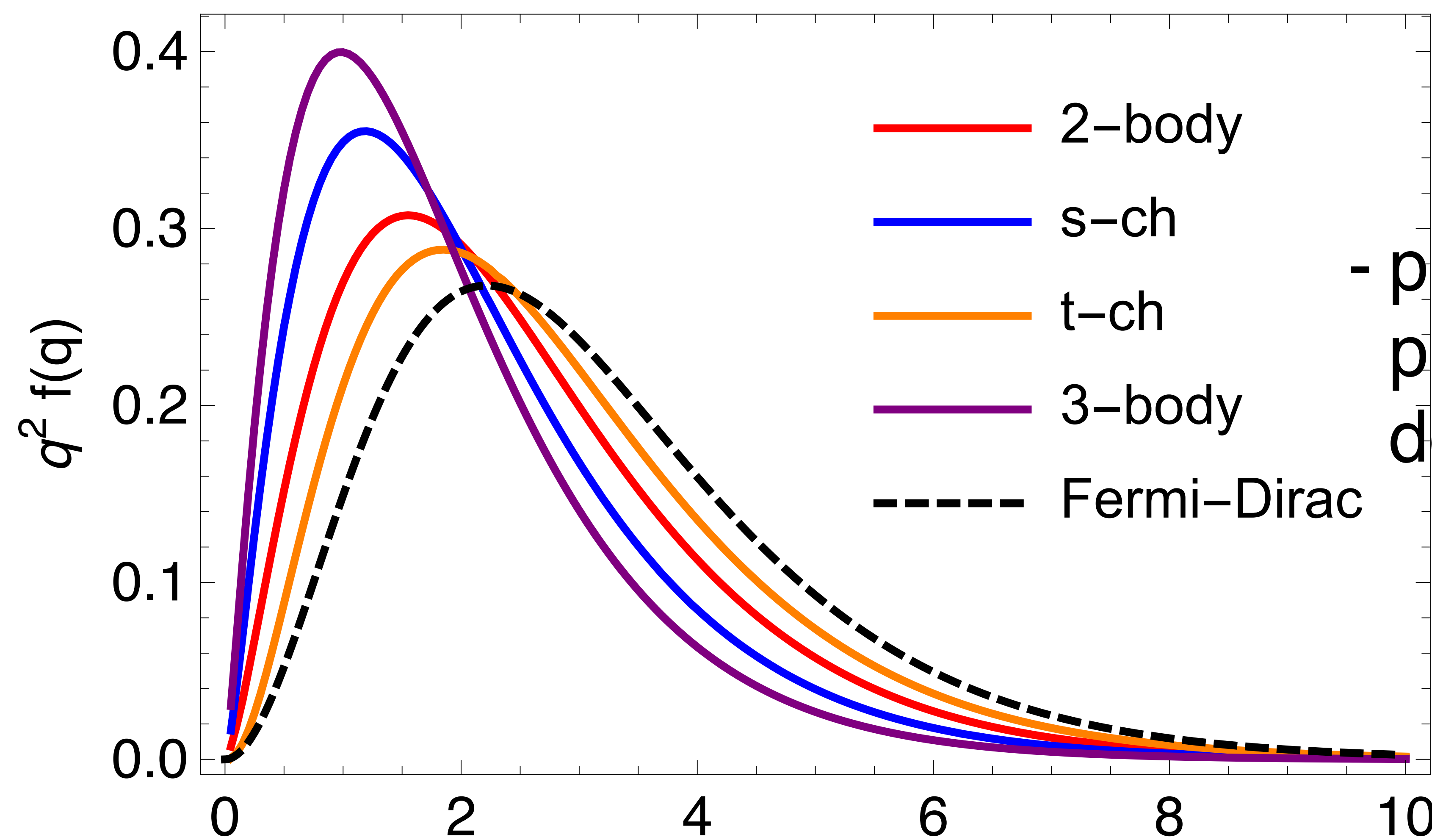
Thermal WDM is much colder than naively expected
→ lower bound on the FIMP mass w/o entropy production is larger

Part 2: Constraining FIMP



DM phase space distribution

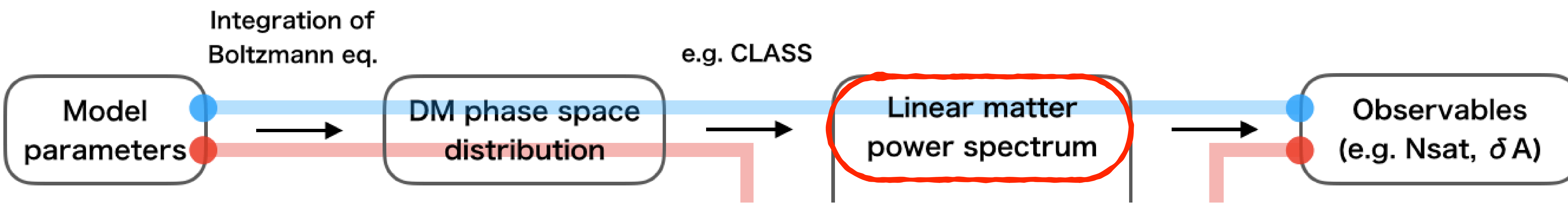
Bae, AK, Liew, and Yanagi, JCAP, 2017



- production process dependent

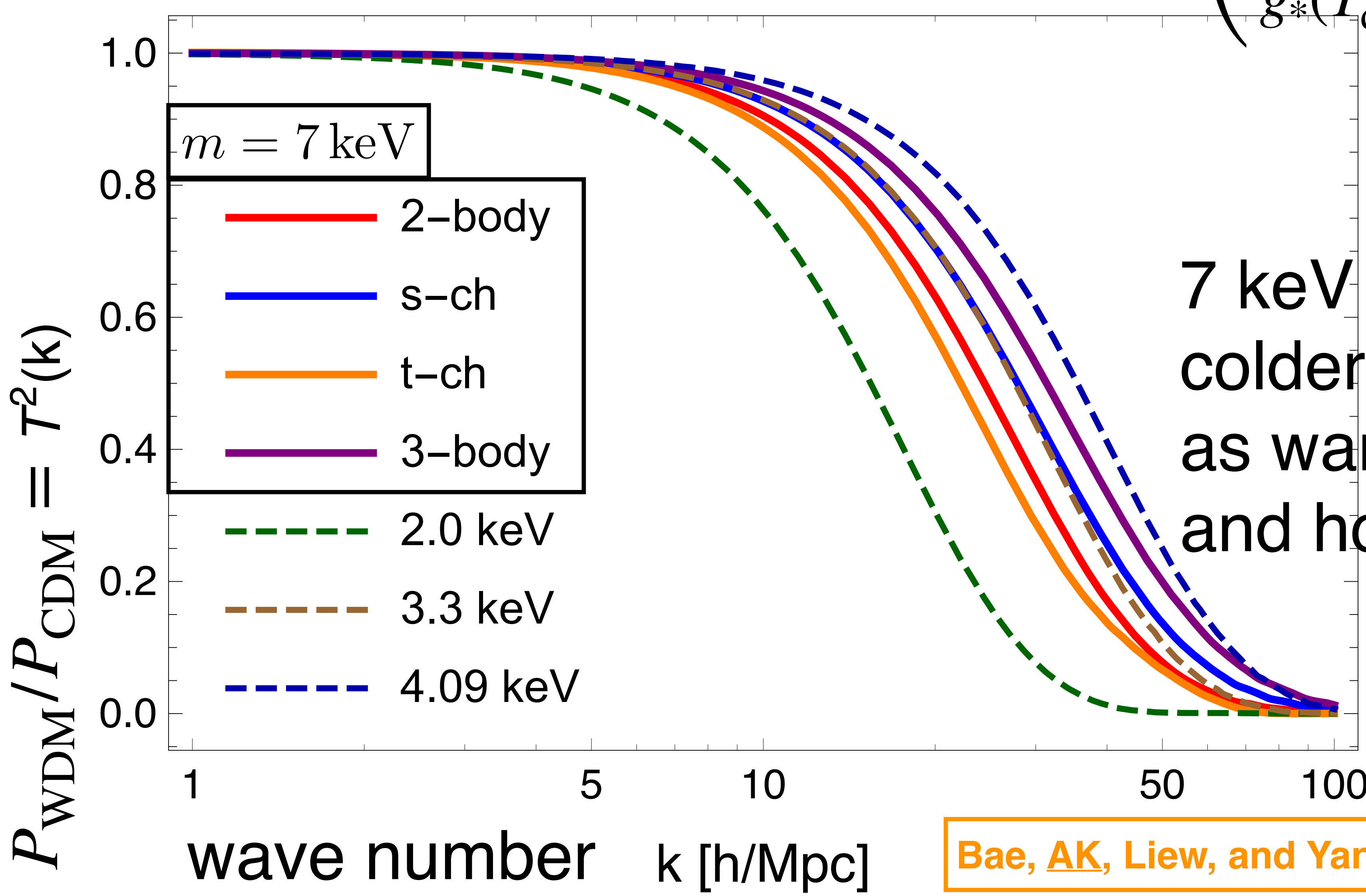
normalized comoving momentum $q = p/T_{\rm DM}$ $\quad T_{\rm DM} = \left(\frac{g_*(T)}{g_*(T_{\rm dec})}\right)^{1/3} T$

7 keV FIMP vs thermal WDM



Linear matter power spectrum

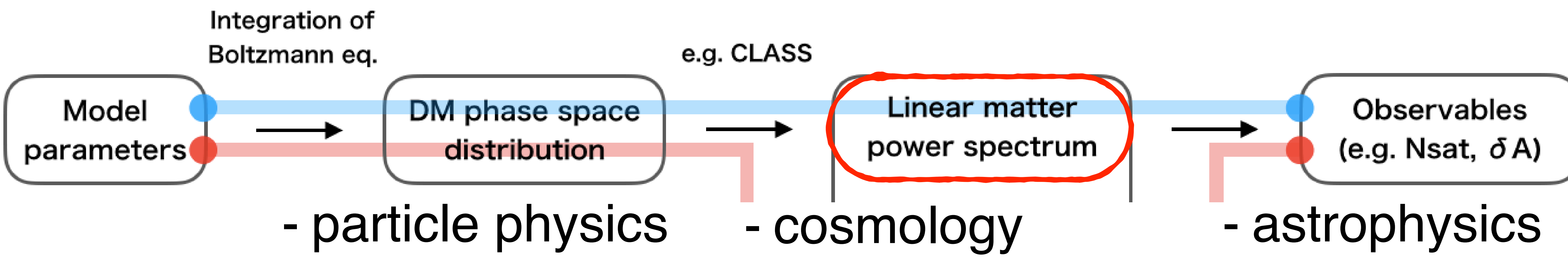
$$T_{\rm DM} = \left(\frac{g_*(T)}{g_*(T_{\rm dec})}\right)^{1/3} T \qquad g_*(T_{\rm dec}) = 106.75$$



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

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

Practical issues



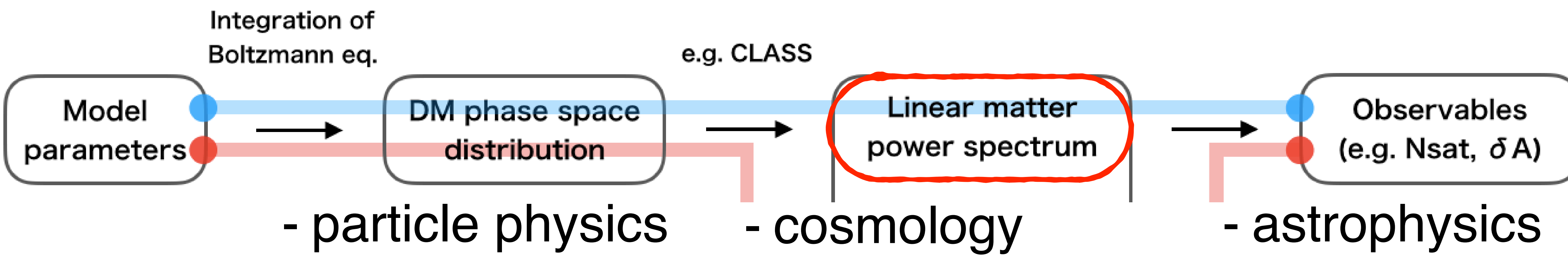
Direct procedure is multidisciplinary and time-consuming

Warmness in structure formation depends on the production mechanism

One has to repeat this procedure on a model-by-model and parameter-by-parameter basis

It is very helpful if one can do some shortcut without losing much precision

Warmness quantity



Quantity characterizes warmness of DM:

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

$$T_{\rm DM} = \left(\frac{g_*(T)}{g_*(T_{\rm dec})}\right)^{1/3} T \qquad g_*(T_{\rm dec}) = 106.75$$

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

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

We can translate $m_{\rm WDM}$ into the FIMP mass m at the level of phase space distribution

Further simplification if we can integrate out the Collision term analytically

Simplified model

$$\mathscr{L}_{\rm F.I.} = -y_\chi \phi \bar{\Psi}\chi - y_f \phi \bar{f} f + \mathrm{h.c.}$$

inspired by the R-parity violating DFSZ axion model

Dine, Fischer, and Srednicki, PLB, 1981

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

χ : DM Majorana fermion — axino

Ψ : heavy Dirac fermion — Higgsino

Kim and Nilles, PLB, 1984

ϕ : heavy scalar — Higgs

Chun, PLB, 1999

Choi, Chun, Hwang, PRD, 2001

f : light Dirac fermion — top quark

Chun and Kim, JHEP, 2006

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

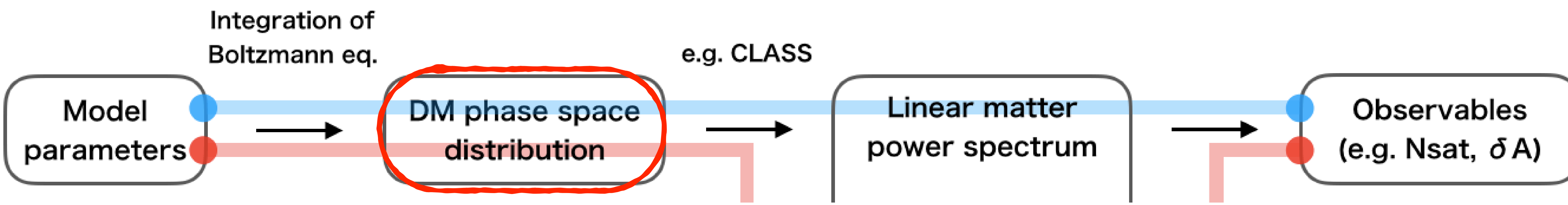
AK and Yanagi, arXiv:1907.04558

decay: $\Psi \to \chi\phi \quad \bar{\Psi} \to \chi\phi^*$

t-channel scattering: $\Psi f \to \chi f \quad \Psi \bar{f} \to \chi \bar{f} \quad \bar{\Psi} f \to \chi f \quad \bar{\Psi}\bar{f} \to \chi \bar{f}$

s-channel scattering: $f\bar{f} \to \chi\Psi \quad f\bar{f} \to \chi\bar{\Psi}$

Analytic results: phase space distribution



$$g_\chi f_{2-\mathrm{body}}(q) = \frac{y_\chi^2 M_0}{4\sqrt{\pi} m_\Psi} \times (1-r^2)^{-1} \left(\frac{q}{1-r^2}\right)^{-\frac{1}{2}} \exp\left(-\frac{q}{1-r^2}\right)$$

$$g_\chi f_{t-\mathrm{ch}}(q) = \frac{y_\chi^2 y_f^2 M_0}{16\pi^{\frac{5}{2}} m_\Psi} \times q^{-\frac{1}{2}} e^{-q} \times \frac{(2-r^2)\tanh^{-1}\sqrt{1-r^2} - \sqrt{1-r^2}}{3(1-r^2)^{\frac{3}{2}}}$$

$$g_\chi f_{s-\mathrm{ch}}(q) = \frac{y_\chi^2 y_f^2 M_0}{16\pi^{\frac{5}{2}} m_\Psi} \times q^{-\frac{1}{2}} e^{-q}$$

$$\times \frac{\pi\left(2+(-3+2q)r^2+r^4\right) \mathrm{Erfc}\left(\sqrt{\frac{q}{1-r^2}}\right) \exp\left(\frac{q}{1-r^2}\right) - 2\sqrt{\pi} r^2 \sqrt{1-r^2} q^{\frac{1}{2}}}{4(1-r^2)^{5/2}}$$

$$r = \frac{m_\phi}{m_\Psi} \qquad H(T_{\mathrm{dec}}) = \sqrt{\frac{\pi^2}{90} g_*(T_{\mathrm{dec}})} \frac{m_\Psi^2}{M_{\mathrm{pl}}} \equiv \frac{m_\Psi^2}{M_0}$$

AK and Yanagi, arXiv:1907.04558

Analytic results: yield

AK and Yanagi, arXiv:1907.04558

$$Y_{\chi,2-\mathrm{body}} \simeq 2 \times \frac{3y_\chi^2 M_1}{32\pi^2 g_{*s}(T_{\mathrm{dec}}) m_\Psi} \left(1 - r^2\right)^2$$

$$Y_{\chi,t-\mathrm{ch}} \simeq 4 \times \frac{3y_\chi^2 y_f^2 M_1}{128\pi^4 g_{*s}(T_{\mathrm{dec}}) m_\Psi} \times \frac{(2 - r^2)\tanh^{-1}\sqrt{1 - r^2} - \sqrt{1 - r^2}}{3(1 - r^2)^{\frac{3}{2}}}$$

$$Y_{\chi,s-\mathrm{ch}} \simeq 2 \times \frac{3y_\chi^2 y_f^2 M_1}{128\pi^4 g_{*s}(T_{\mathrm{dec}}) m_\Psi} \times \frac{r(3 - r^2) + (-3 + 2r^2 + r^4)\tanh^{-1}(r)}{2r^5}$$

$$r = \frac{m_\phi}{m_\Psi} \qquad H(T_{\mathrm{dec}}) = \sqrt{\frac{\pi^2}{90} g_*(T_{\mathrm{dec}})} \frac{m_\Psi^2}{M_{\mathrm{pl}}} \equiv \frac{m_\Psi^2}{M_0} \qquad M_1 = \frac{45}{2\pi^2} M_0$$

Analytic results: warmness

AK and Yanagi, arXiv:1907.04558

$$m_\chi = 7\,\mathrm{keV}\left(\frac{m_{\mathrm{WDM}}}{2.5\,\mathrm{keV}}\right)^{\frac{4}{3}}\left(\frac{\tilde{\sigma}_\chi}{3.6}\right)\left(\frac{106.75}{g_{*s}(T_{\mathrm{dec}})}\right)^{\frac{1}{3}}$$

$$\tilde{\sigma}_\chi^2 = \frac{Y_{\chi,2-\mathrm{body}}}{Y_\chi}\tilde{\sigma}^2_{\chi,2-\mathrm{body}} + \frac{Y_{\chi,t-\mathrm{ch}}}{Y_\chi}\tilde{\sigma}^2_{\chi,t-\mathrm{ch}} + \frac{Y_{\chi,s-\mathrm{ch}}}{Y_\chi}\tilde{\sigma}^2_{\chi,s-\mathrm{ch}}$$

$$\tilde{\sigma}^2_{\chi,2-\mathrm{body}} = \frac{35}{4}(1-r^2)^2$$

$$\tilde{\sigma}^2_{\chi,t-\mathrm{ch}} = \frac{35}{4}$$

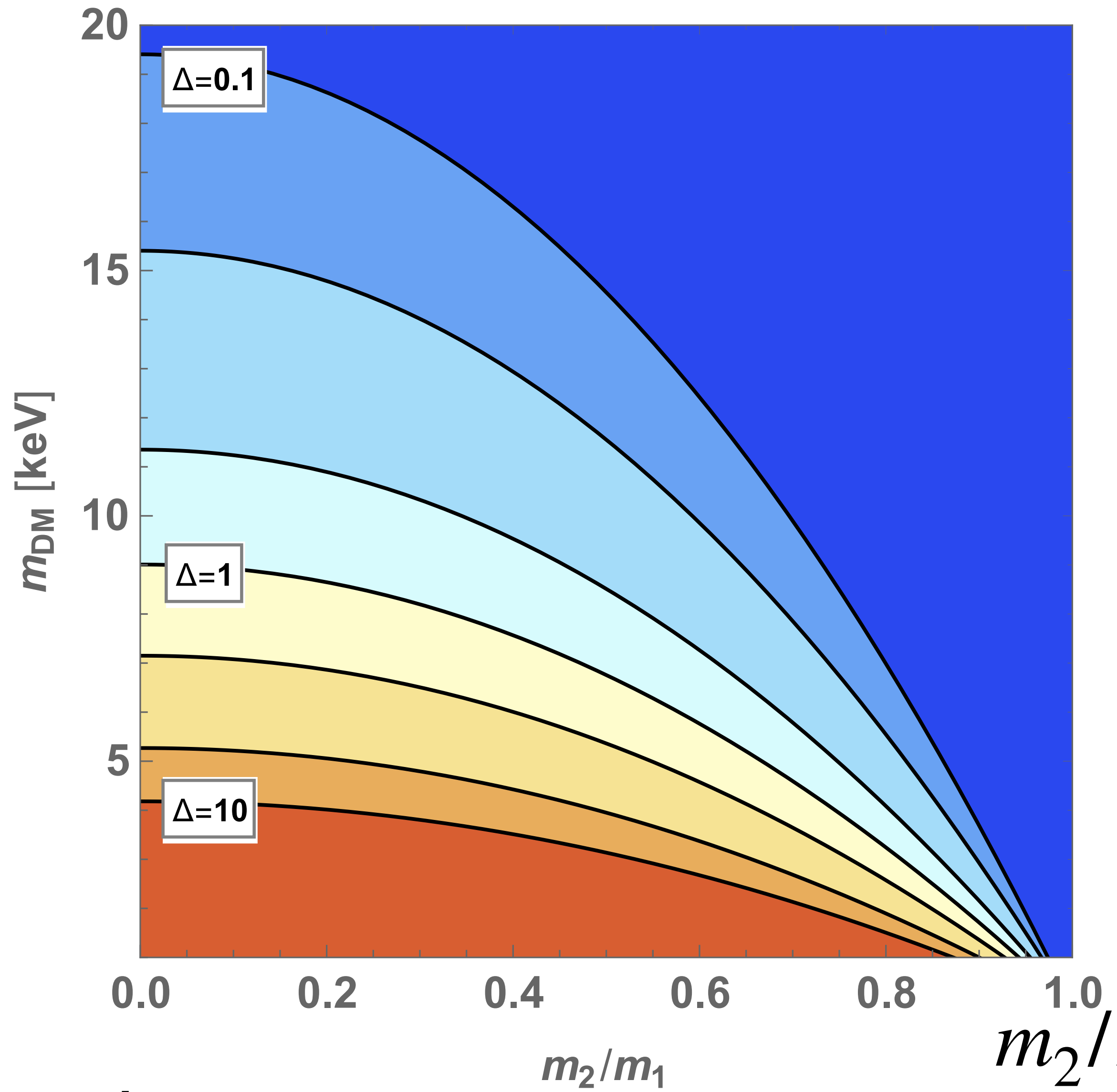
$$\tilde{\sigma}^2_{\chi,s-\mathrm{ch}} = \frac{7(105r - 265r^3 + 191r^5 - 15r^7 - 15(1-r^2)^3(7+r^2)\tanh^{-1} r)}{12r^4(r(3-r^2) + (-3+2r^2+r^4)\tanh^{-1} r)}$$

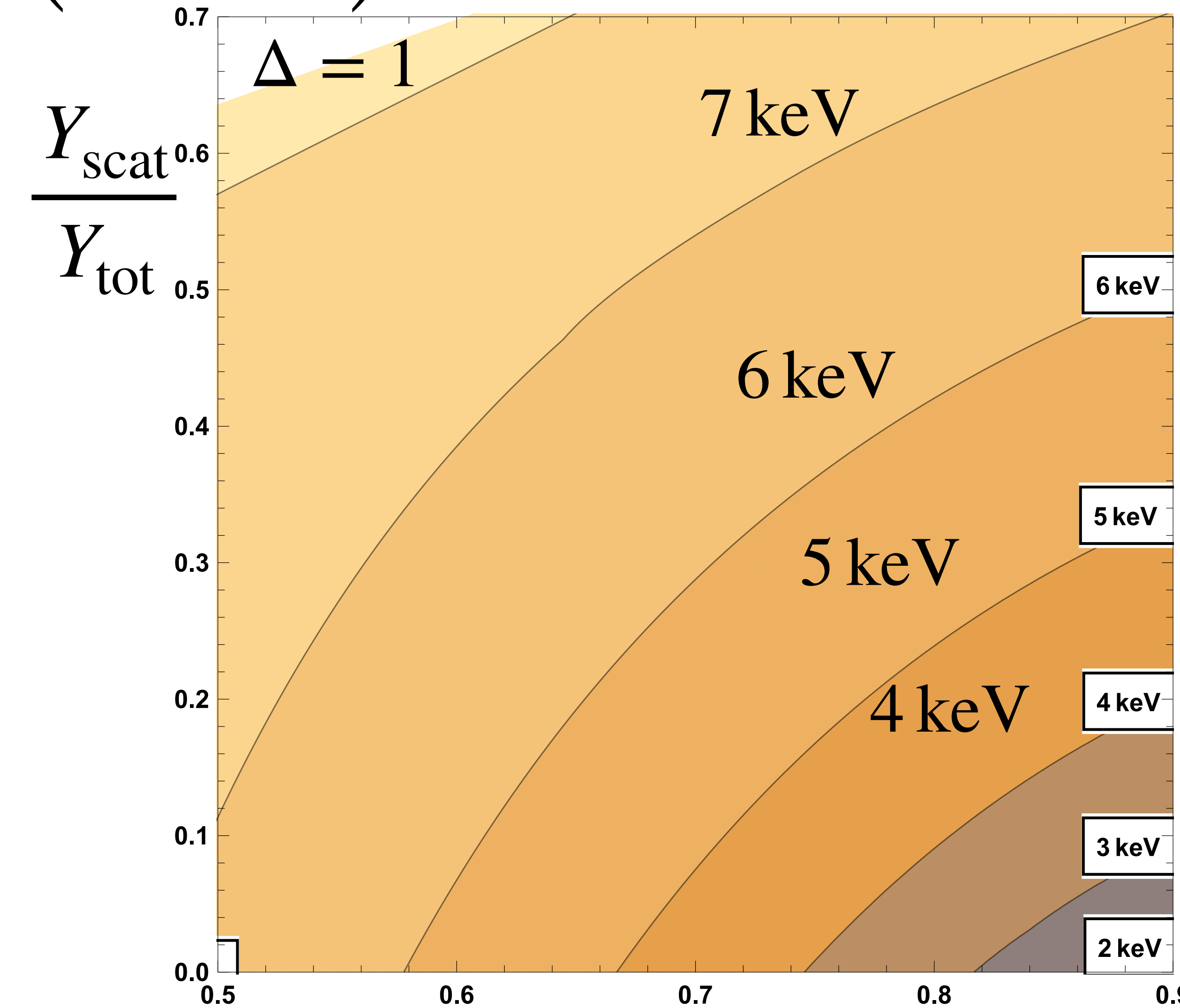
$$r = \frac{m_\phi}{m_\Psi} \qquad H(T_{\mathrm{dec}}) = \sqrt{\frac{\pi^2}{90}g_*(T_{\mathrm{dec}})}\frac{m_\Psi^2}{M_{\mathrm{pl}}} \equiv \frac{m_\Psi^2}{M_0} \qquad M_1 = \frac{45}{2\pi^2}M_0$$

Analytic mapping through warmness

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

$$T_{\rm DM} = \left(\frac{g_*(T)}{\Delta g_*(T_{\rm dec})}\right)^{1/3} T \qquad g_*(T_{\rm dec}) = 106.75$$





m_2/m_1

Bae, Jinno, AK, and Yanagi, arXiv:1906.09141

m_2/m_1

decay: $\underset{m_1}{\Psi} \to \chi \underset{m_2}{\phi} \qquad \bar{\Psi} \to \chi\phi^*$

- mass degeneracy between Ψ and ϕ makes χ colder

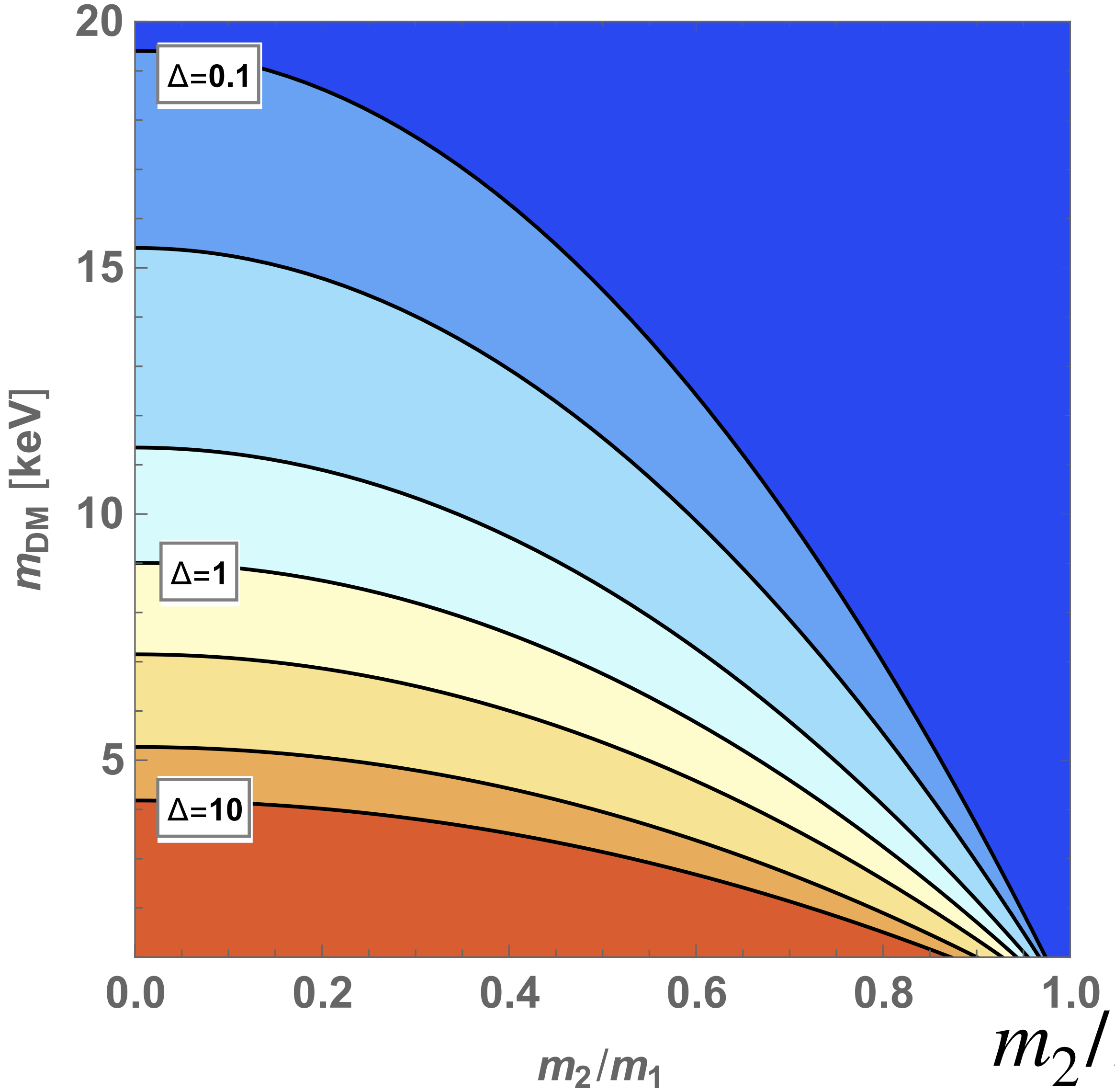
7 keV FIMP DM is disfavored by the current Lyman-α forest data w/o entropy production or mass degeneracy

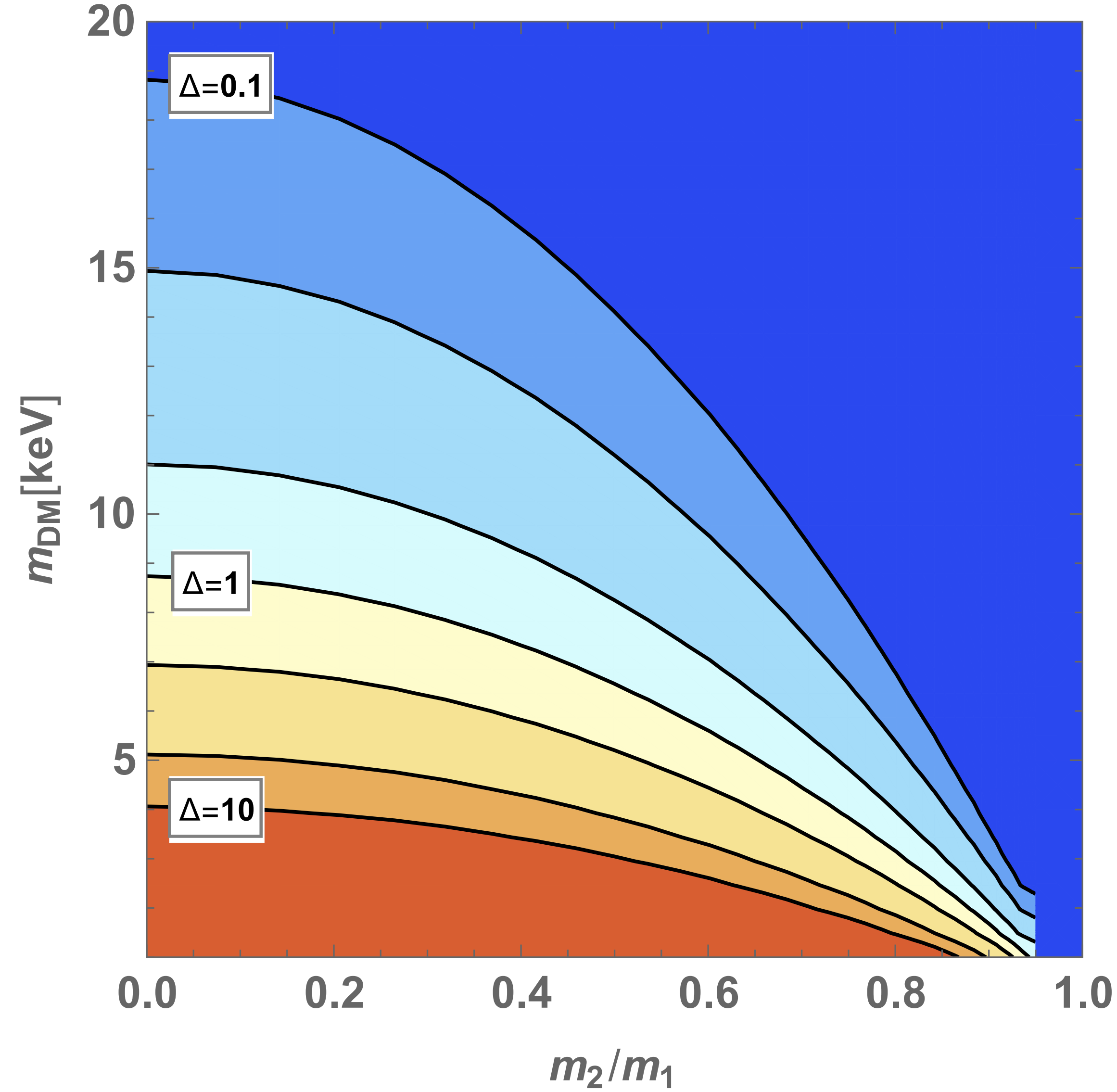
Analytic vs full

$\boxed{m_{\rm WDM} = 3.5\,{\rm keV}}$ $T_{\rm DM} = \left(\frac{g_*(T)}{\Delta g_*(T_{\rm dec})}\right)^{1/3} T$ $g_*(T_{\rm dec}) = 106.75$

Bae, Jinno, AK, and Yanagi, arXiv:1906.09141

$m_{\rm DM}$ [keV]





m_2/m_1

- analytic through warmness quantity σ^2
- direct procedure

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

Summary

Light (keV-scale) FIMPs are of particular interest

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

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 quantity σ^2
    - only phase-space distribution is needed
    - analytic formulas available in a simplified model

Thank you for your attention

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: electoweak-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 electoweak-scale new physics that explains the origin of the weak scale against Planck scale (hierarchy problem)

- collider experiments

Pragmatic WIMP

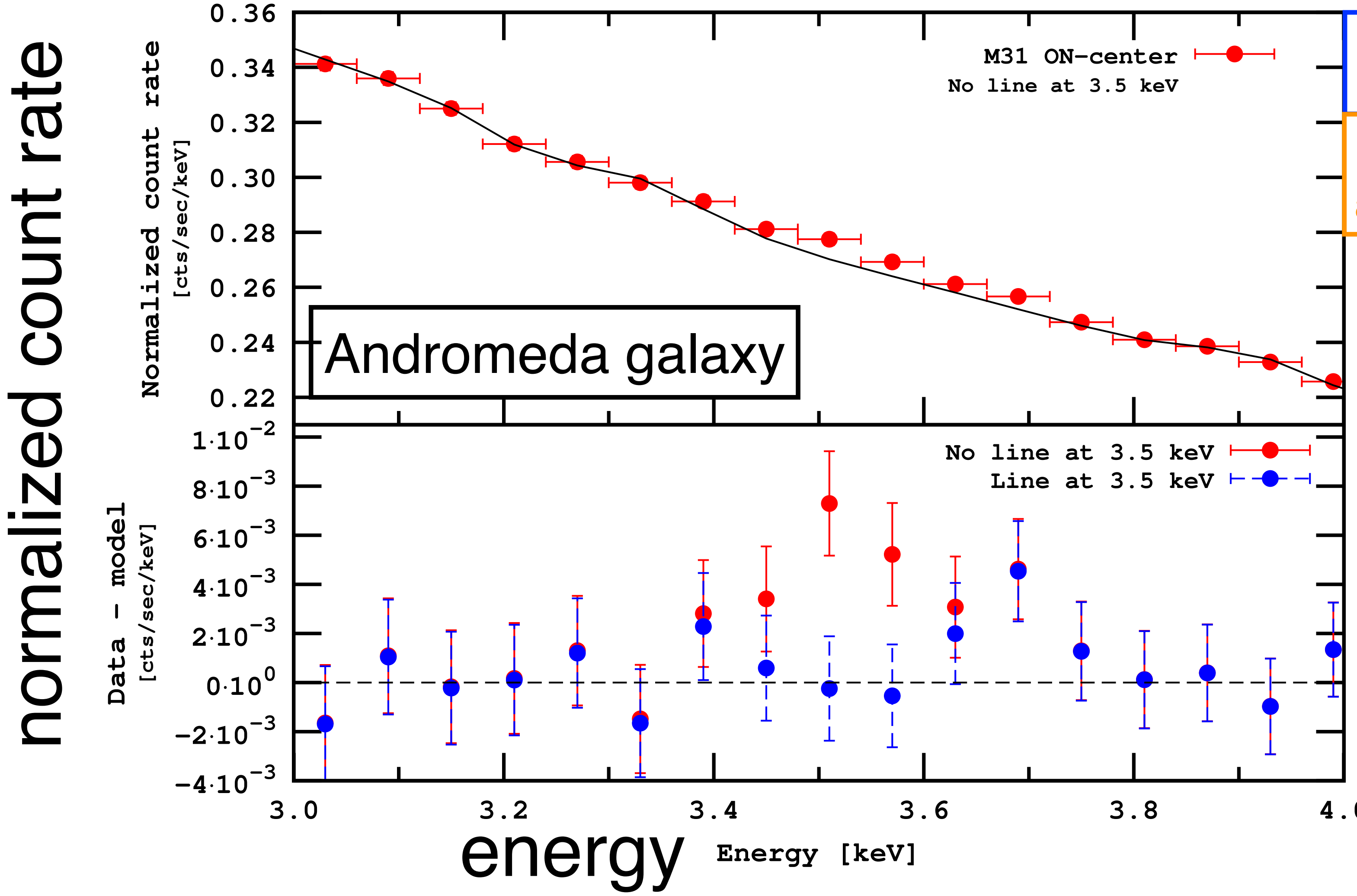
LHC null-detection of electroweak-scale new physics

- something wrong in naturalness and postulated solutions
- no convincing reason for new physics at the electroweak 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)

3.5 keV line excess



XMM-Newton

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

- continuum (w/ instrumental)

- +3.5 keV line

Chandra | Andromeda galaxy

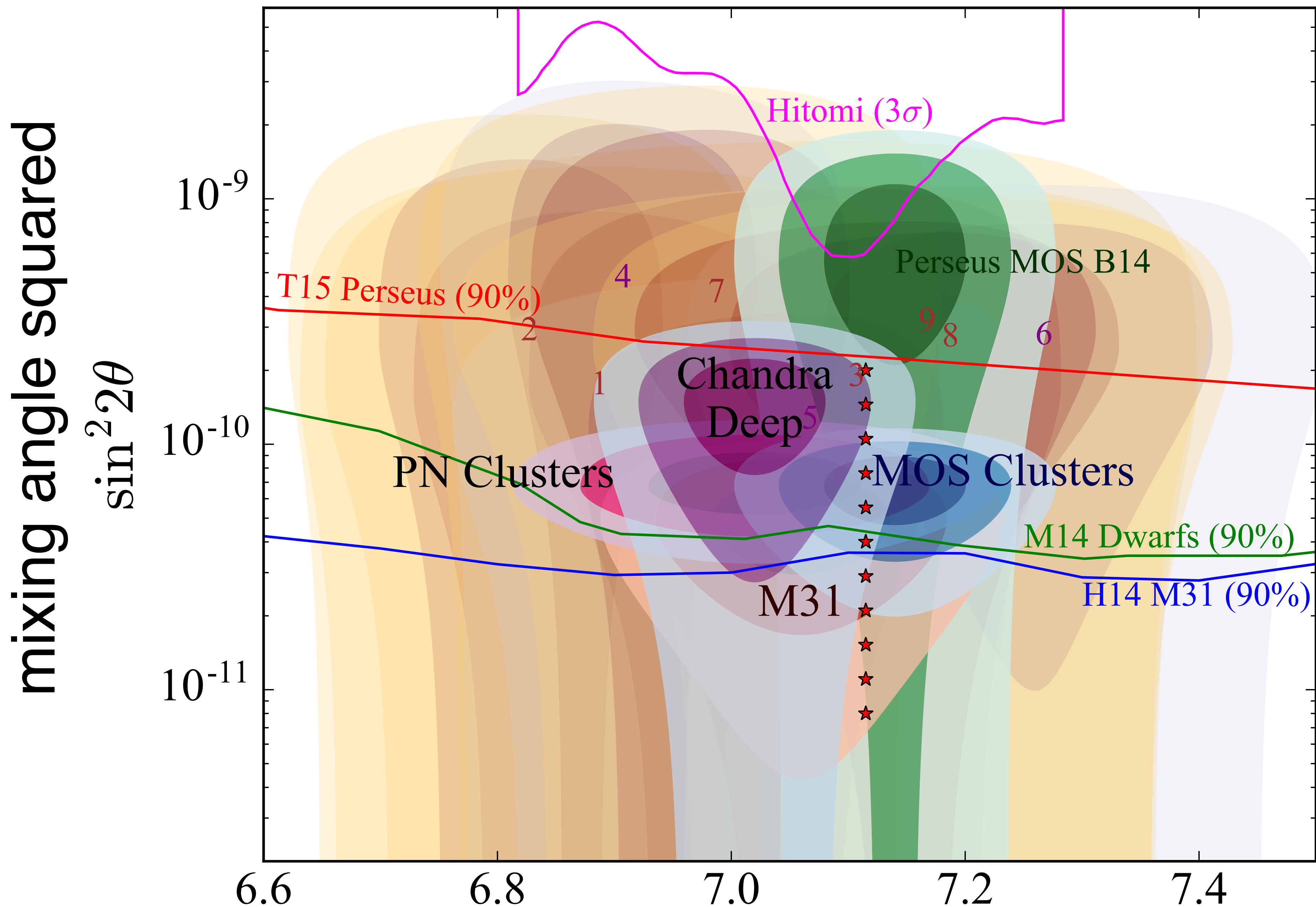
Horiuchi *et al.*, PRD, 2014

null-detection

3.5 keV line excess is found in some instruments, but not in others; in some objects, but not in others

3.5 keV line status

Sterile neutrino: SM singlet (e.g. right-handed neutrino) slightly mixed w/ left-handed neutrino $G_F \to \theta G_F$



- shaded regions: explain 3.5 keV line excess

- lines: constraints from null-detection

Abazajian, Phys. Rept. 2017

Dodelson *et al.*, PRL, 1994

Oscillation from left-handed neutrino (Dodelson-Widrow mechanism) →

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

Example: light axino

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

- dynamically explaining why CP is a good symmetry in strong interaction $v_{\rm PQ} = f_a N_{\rm DW} \sim 10^9\text{-}10^{12}\,{\rm GeV}$

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

Dine, Fischer, and Srednicki, PLB, 1981 | Zhitnitsky, Sov. J. Nucl. Phys. B, 1980

DFSZ axion model: PQ-charge assignment of SM fields

Kim and Nilles, PLB, 1984 | Chun, PLB, 1999 | Choi, Chun, Hwang, PRD, 2001 | Chun and Kim, JHEP, 2006

$$Q_{\rm PQ}\{X,\, H_u,\, H_d,\, L,\, \bar{E},\, Q,\, \bar{U},\, \bar{D}\} = \{-1,\, 1,\, 1,\, 2,\, -3,\, 0,\, -1,\, -1\}$$

- explaining why $\mu \sim v_{\rm PQ}^2/M_*$ term is at the TeV scale
- long lifetime of proton w/o R parity $\lambda'\lambda'' < 10^{-27}\left(\frac{m_s}{\rm TeV}\right)^3$

$$\lambda \sim \lambda' \sim v_{\rm PQ}/M_* \quad \lambda'' \sim v_{\rm PQ}^3/M_*^3 \quad M_* \sim 10^{16}\,{\rm GeV}$$

Light axino interaction

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

Bilinear R parity violating interaction → axino-neutrino mixing

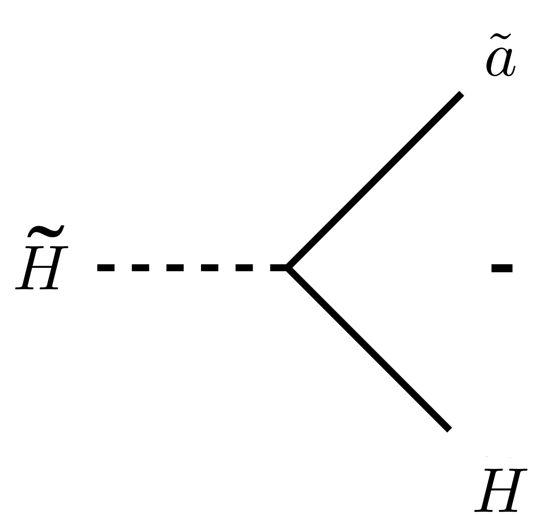
$$\mu' = \epsilon\mu \sim v_{\rm PQ}^3/M_*^2$$

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

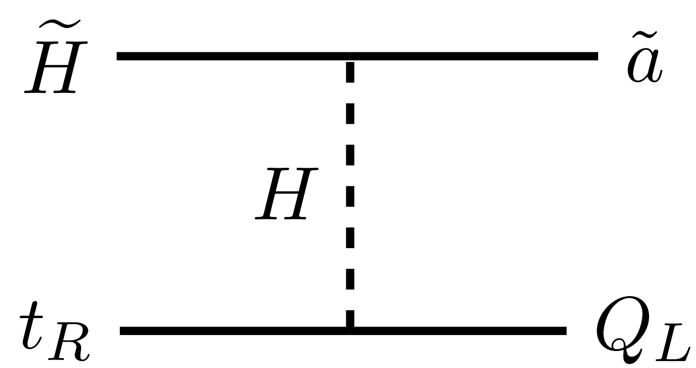
- axino as sterile neutrino

R parity preserving interaction → freeze-in production of axino

$$W_{\rm int} = \frac{2\mu}{v_{\rm PQ}} A H_u H_d \qquad \Omega_{\tilde a} h^2 \simeq 0.5\left(\frac{\mu}{500\,{\rm GeV}}\right)\left(\frac{2.5\times 10^{10}\,{\rm GeV}}{v_{\rm PQ}}\right)^2\left(\frac{m_{\tilde a}}{7\,{\rm keV}}\right)$$



- 2-body decay



- scattering (+ s-channel)

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) $m_{\rm WDM} = \mathcal{O}(1)\,{\rm keV}$
- beyond WIMP?

Warmness

Quantity characterizes warmness of DM:

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

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

$$T_{\rm DM} = \left(\frac{g_*(T)}{g_*(T_{\rm dec})}\right)^{1/3} T \qquad g_*(T_{\rm dec}) = 106.75$$

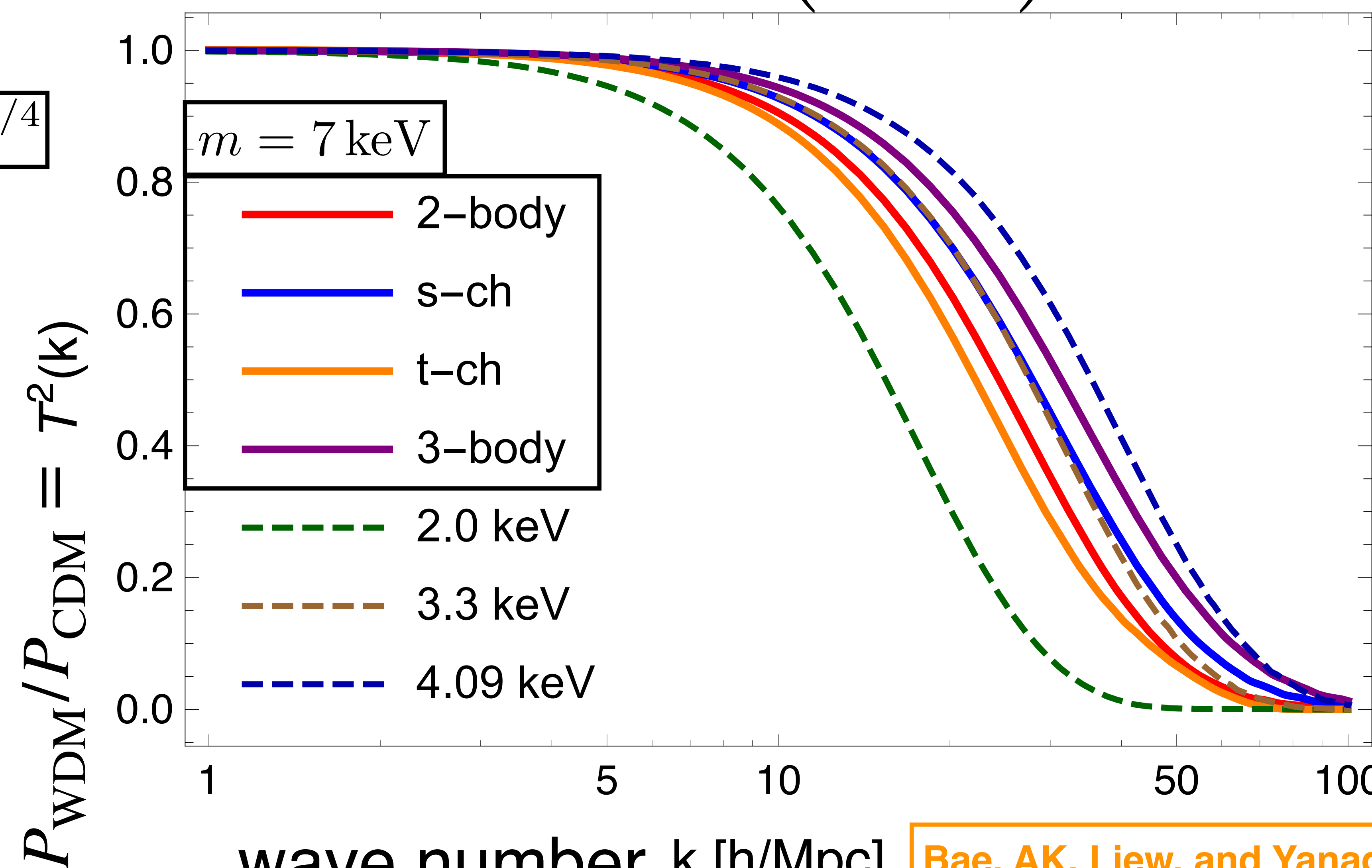
$2.5\,\mathrm{keV}(\tilde{\sigma}/3.6)^{-3/4}$

$= 2.9\,\mathrm{keV}$

$= 3.2\,\mathrm{keV}$

$= 2.7\,\mathrm{keV}$

$= 3.6\,\mathrm{keV}$



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

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

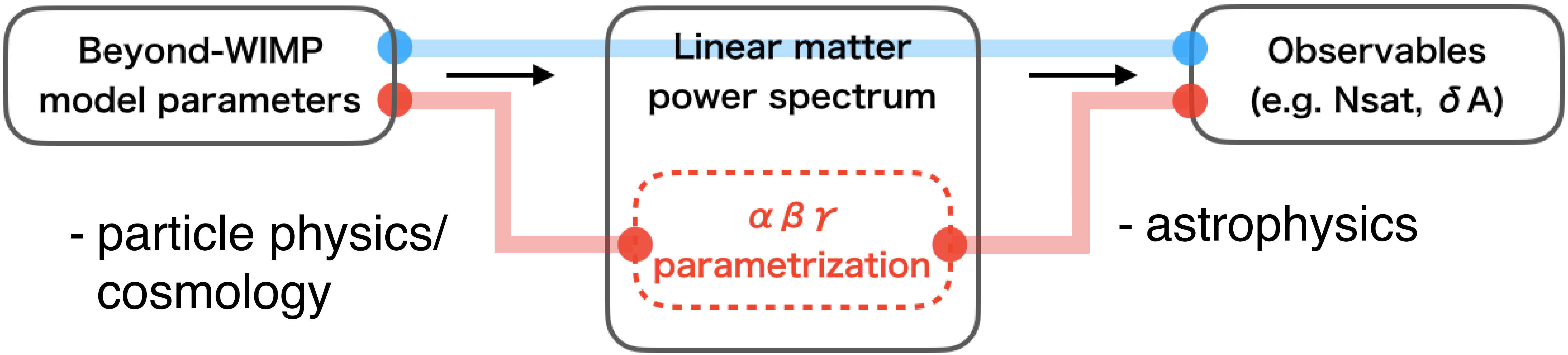
Hu, Barkana, and Gruzinov, PRL, 2000

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

ETHOS collaboration, PRD, 2016 and MNRAS, 2016

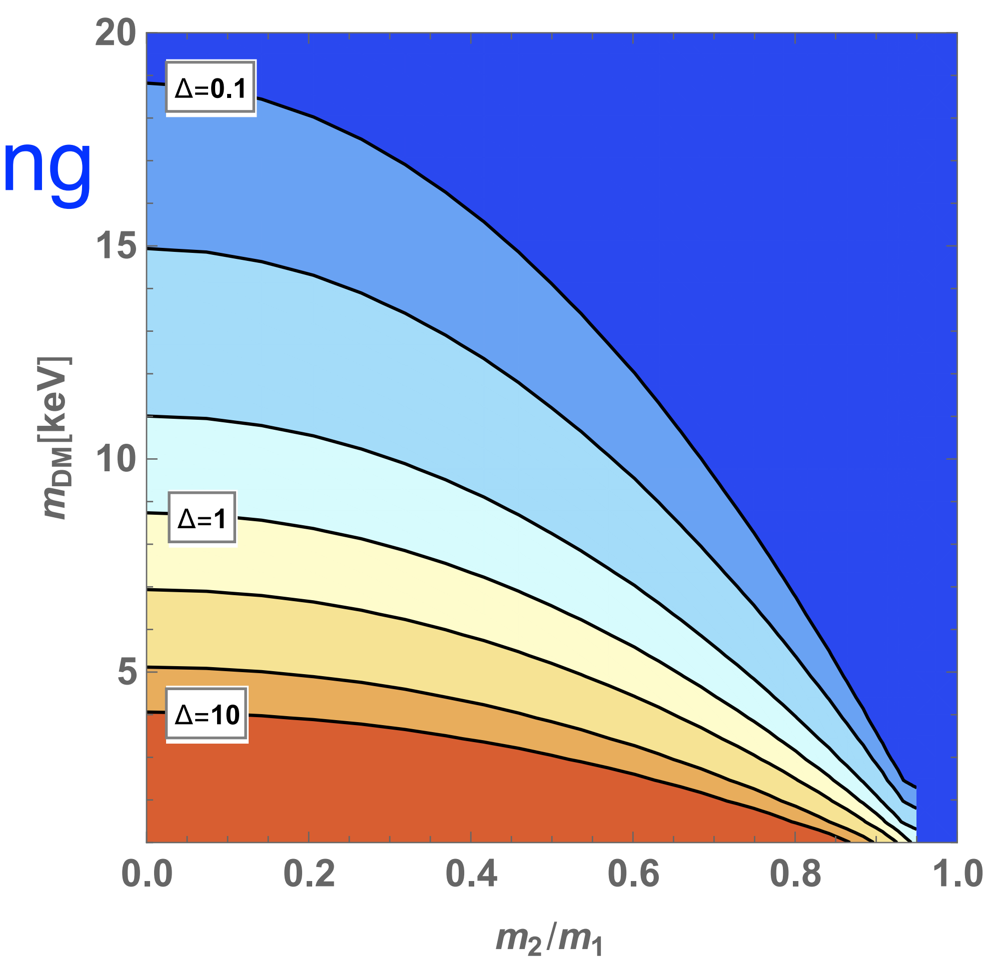
Two-step approach

Bae, Jinno, AK, and Yanagi, in preparation

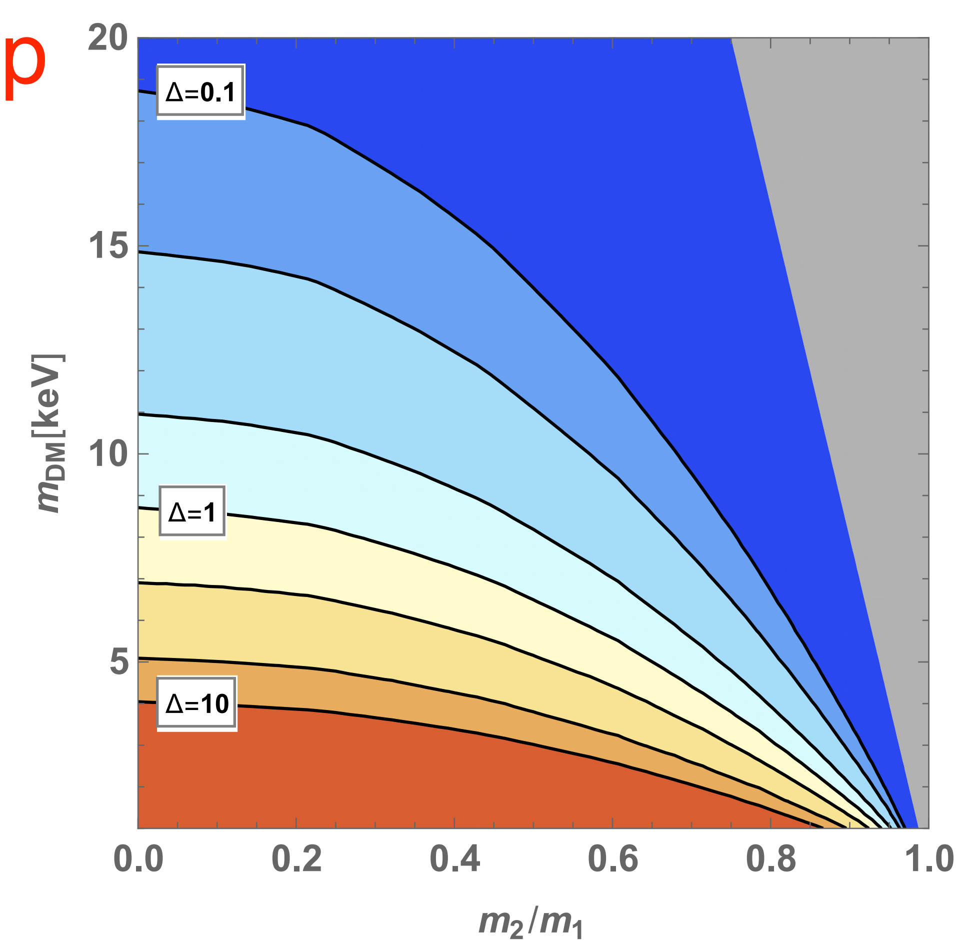


Three parameters → not easy to share results → Machine learning!

- direct modeling



- two-step via ML



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**

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

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

Peccei *et al.*, PRL, 1977

Peccei *et al.*, PRD, 1977

Weinberg, PRL, 1978

Wilczek, PRL, 1978

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

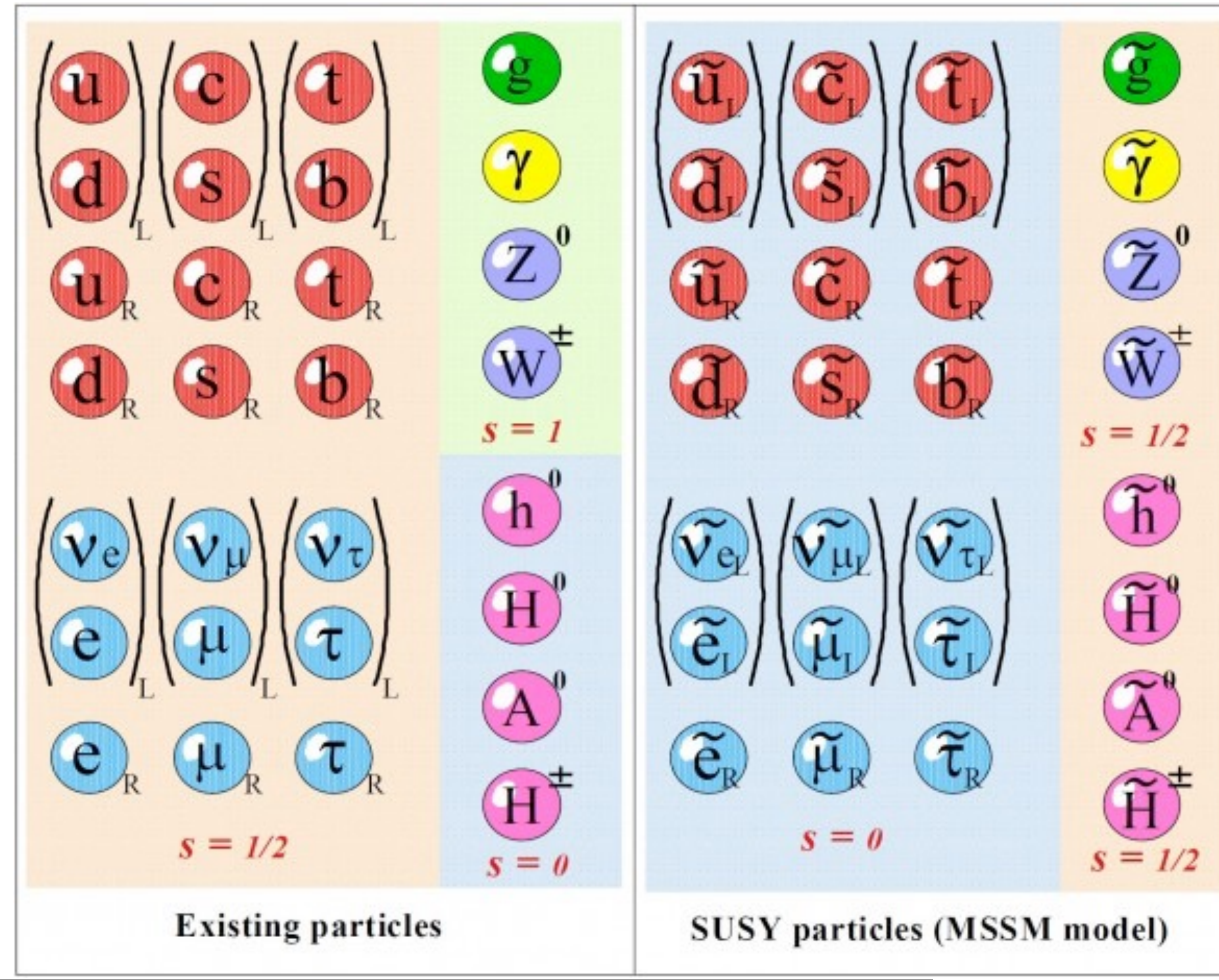
Dine *et al.*, PLB, 1981 | Zhitnitsky, Sov. J. Nucl. Phys. B, 1980

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 (s) — axino ($\tilde{a}$)



Martin, arXiv:hep-ph/9709356

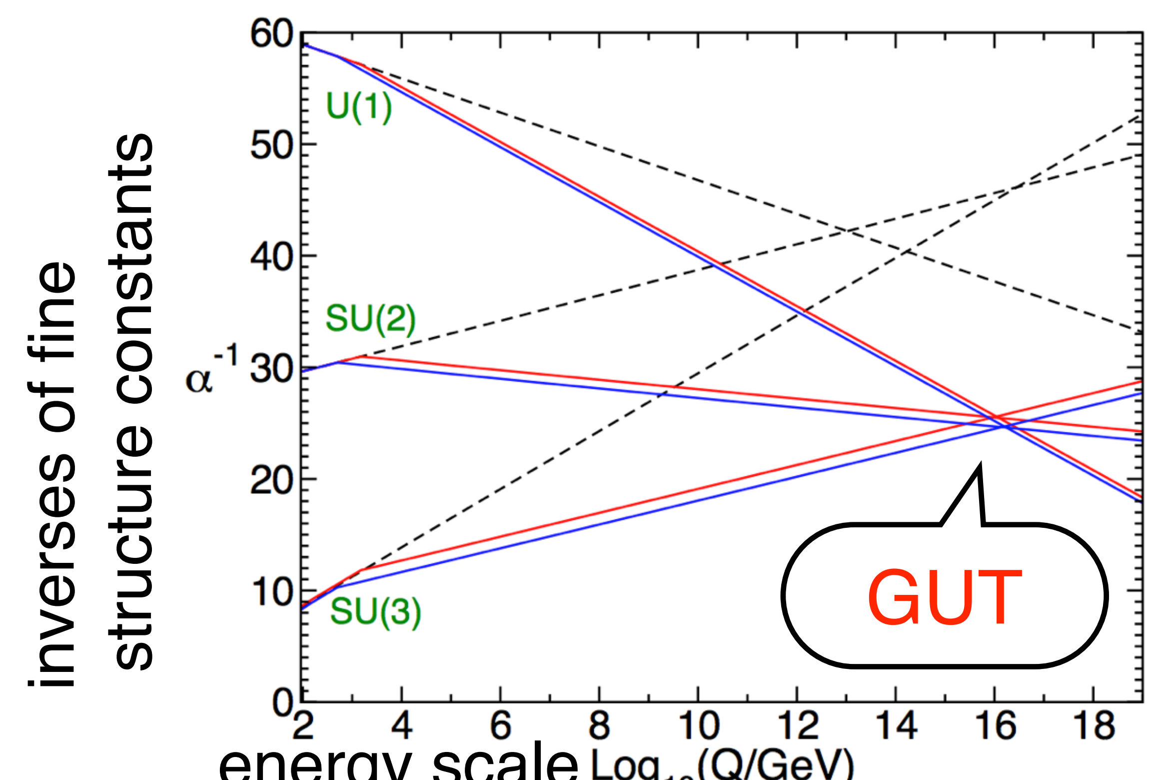
supersymmetric extension of the SM: MSSM

→ achieve grand unification

→ solve the **large hierarchy problem**

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

- $m^2_{h^0}$: model prediction $(126\ \mathrm{GeV})^2$
- $m^2_{h^0,0}$: model parameter
- $\Delta(m^2_{h^0})$: 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:

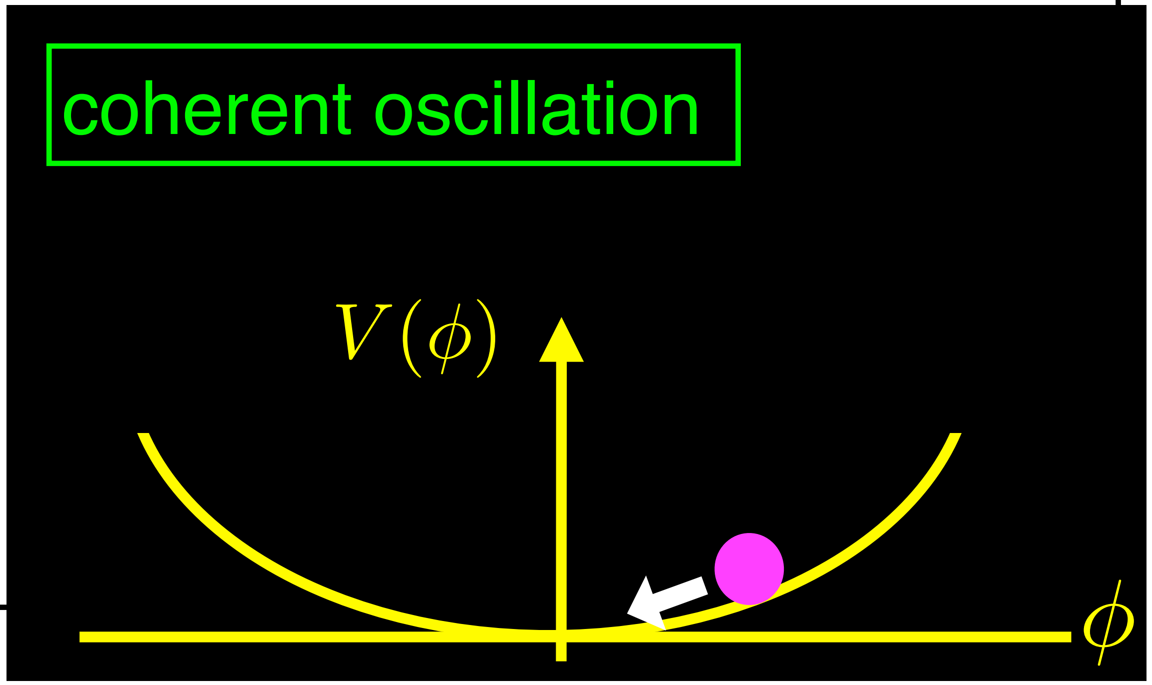
Raffelt, Lect. Notes Phys., 2008

- 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

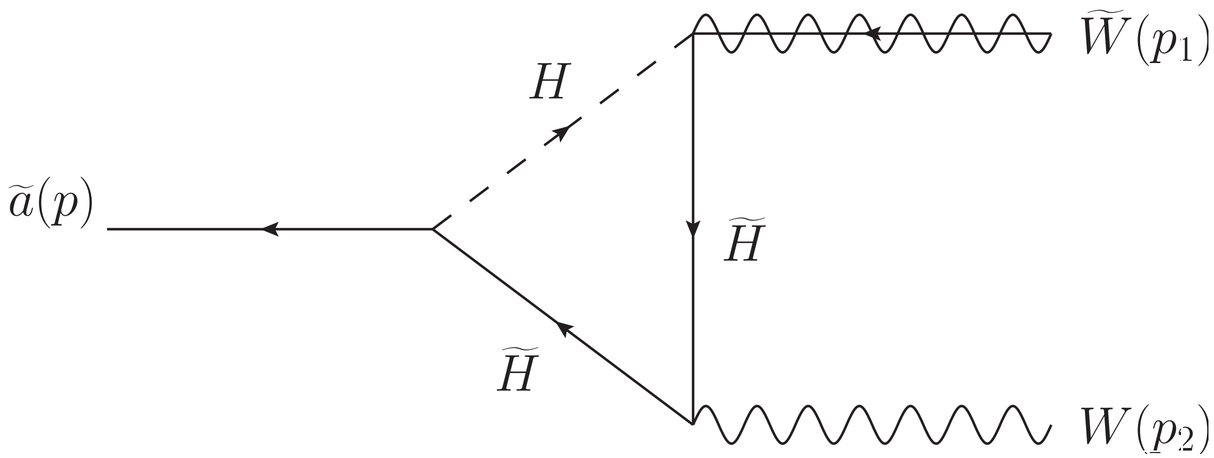


Anomalous coupling

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

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

one particle irreducible (1PI) diagram



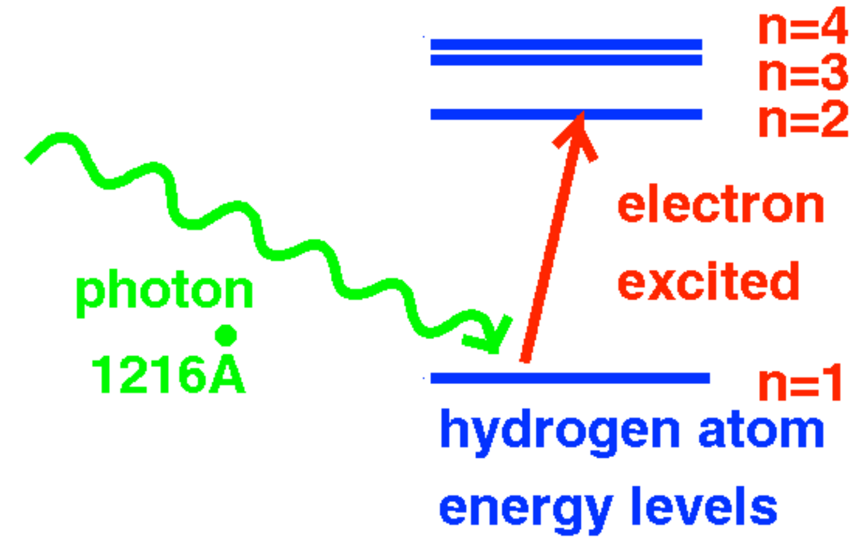
$$\propto \frac{\mu^2}{p^2} \quad \text{for} \quad p^2 \gg \mu^2$$

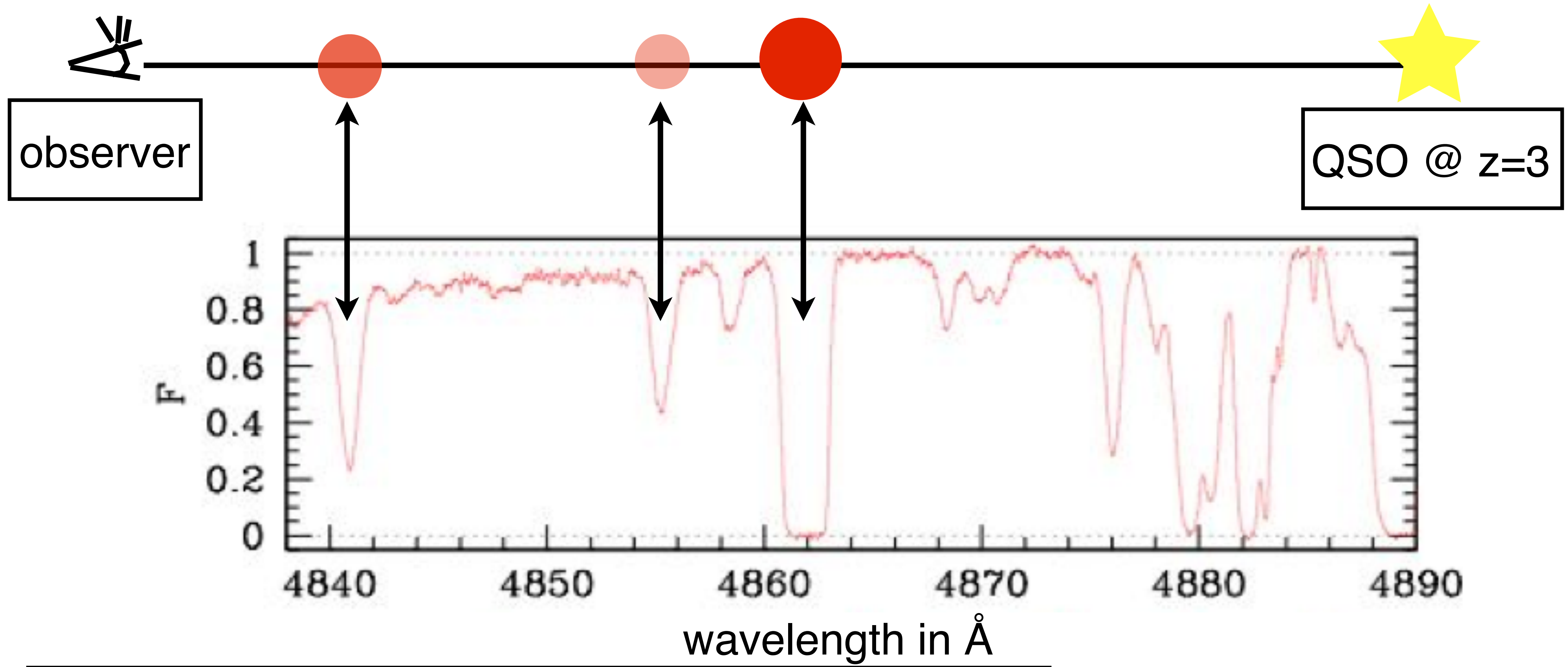
Bae *et al.*, JHEP, 2011 | Bae *et al.*, JCAP, 2012

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

Lyman-alpha forest as a probe of matter distribution

absorption intensity/frequency
↔ HI distribution along the line-of-sight





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

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

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:

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

Hubble expansion

collision term

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

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

sum over all the processes