Particle dark matter: WIMP and beyond

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July 22, 2019 @ CTPU summer school

What I will discuss

Introduction to dark matter — part 1

- observational evidences
- no candidate in the SM

Pre-LHC: WIMP miracle — part 2

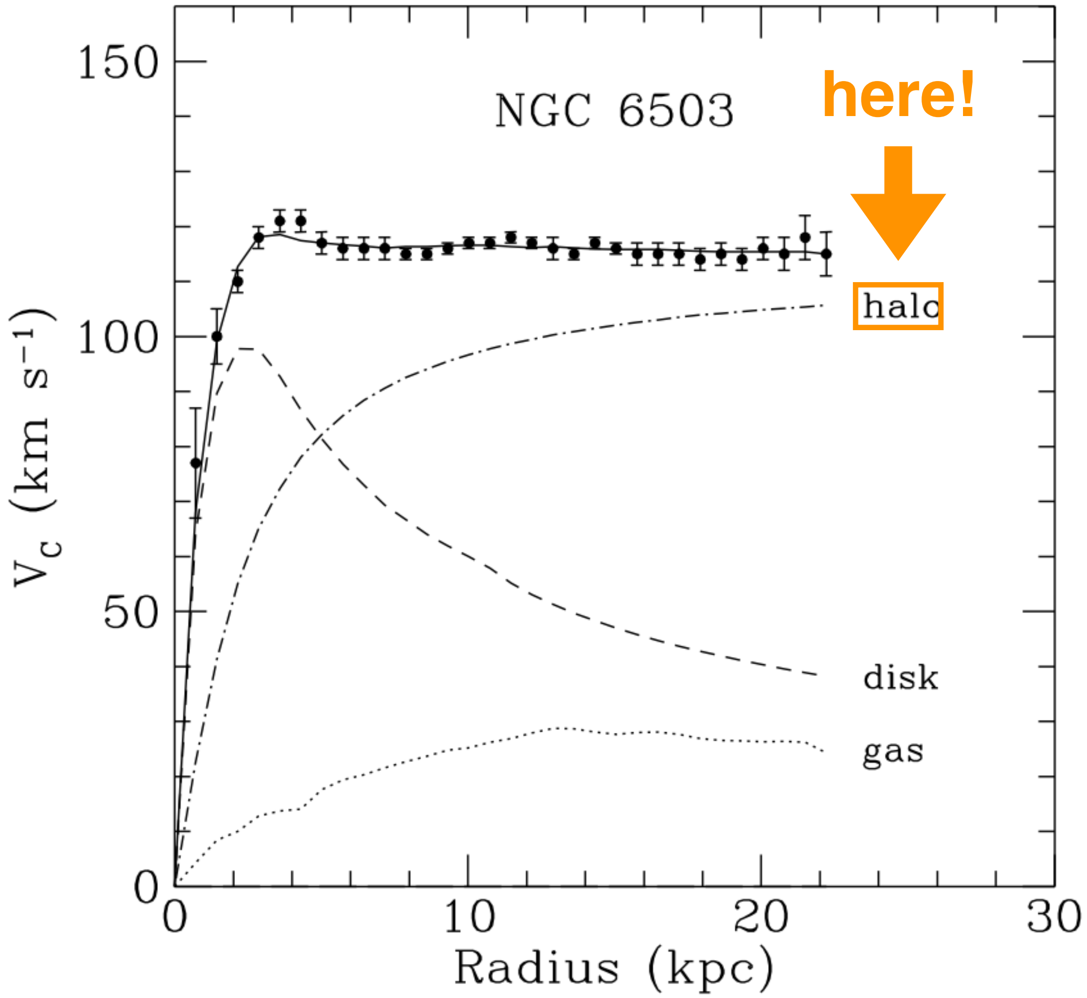
- naturalness of the SM
- thermal freeze-out

Post-LHC: brainstorming — part 3

- top-down: new reasoning for WIMP?
- bottom-up: structure formation of the Universe?

Introduction to dark matter

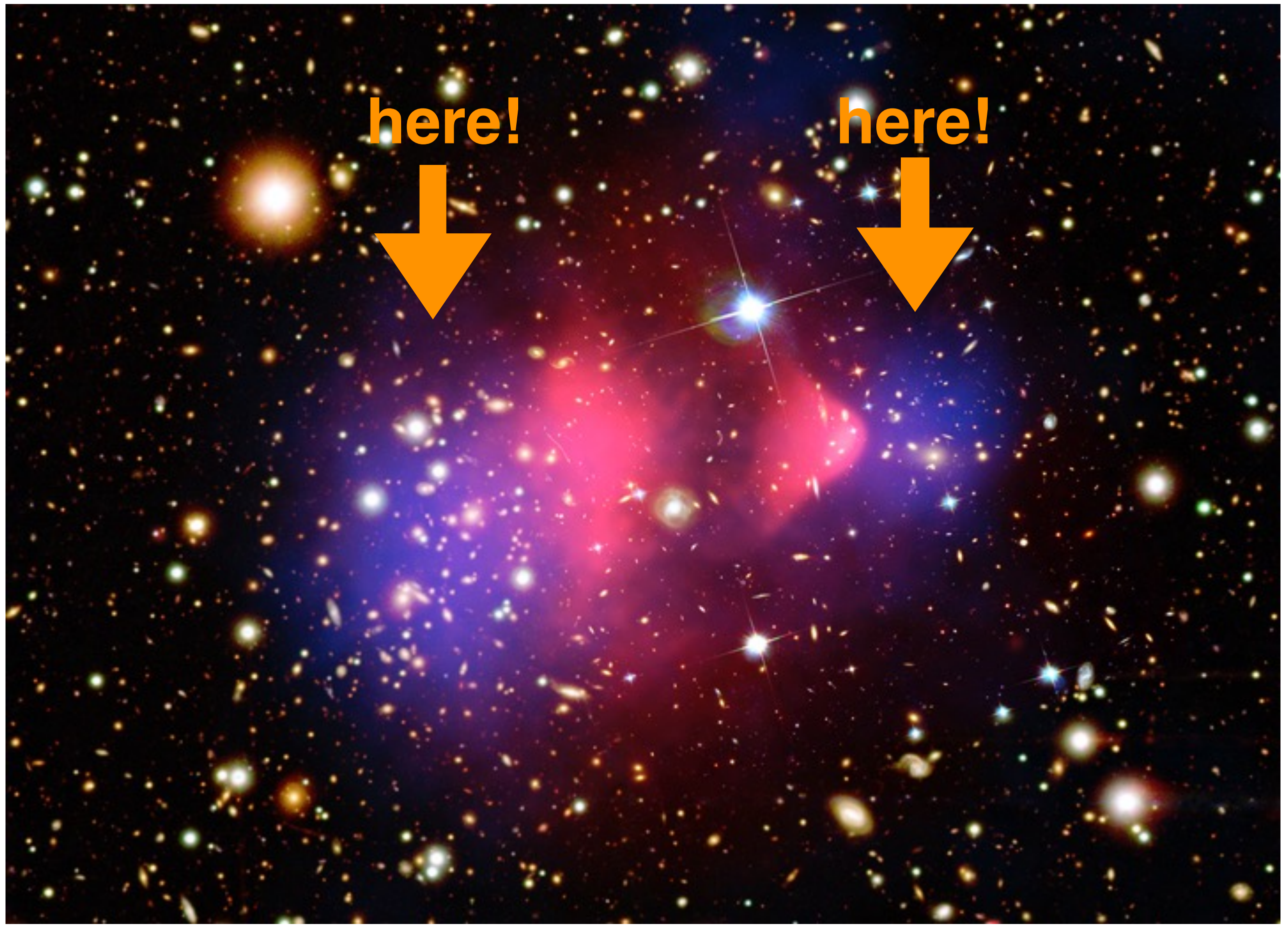
Dark matter



- galactic rotation curves

Accumulated observational evidences of a new form of matter: dark matter (DM)

- bullet clusters

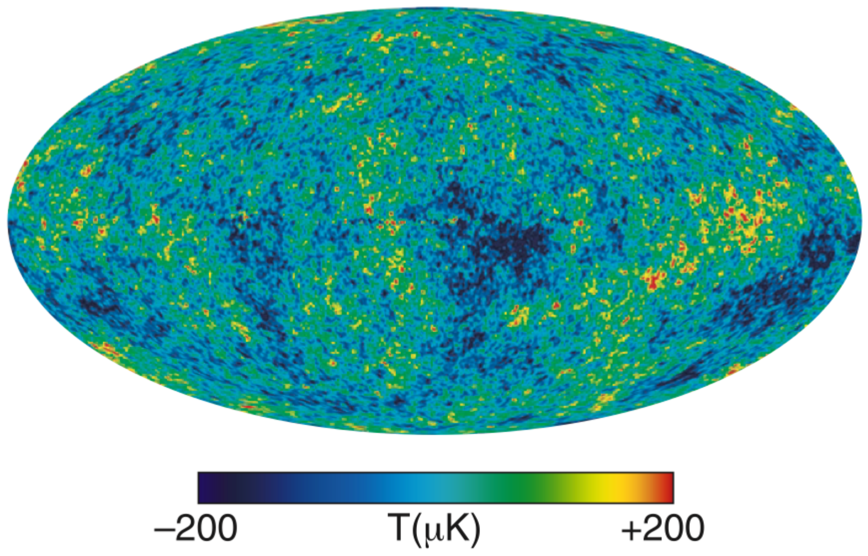


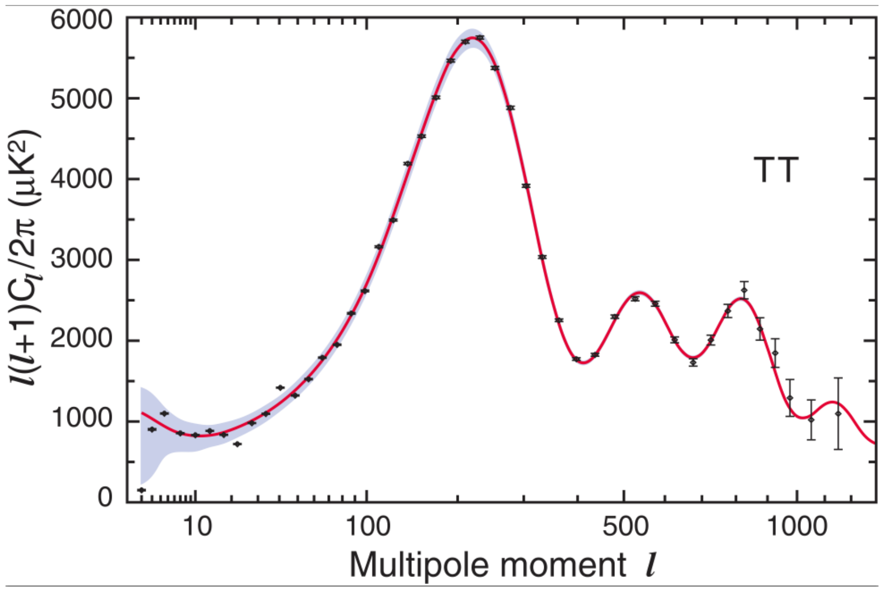
Dark matter

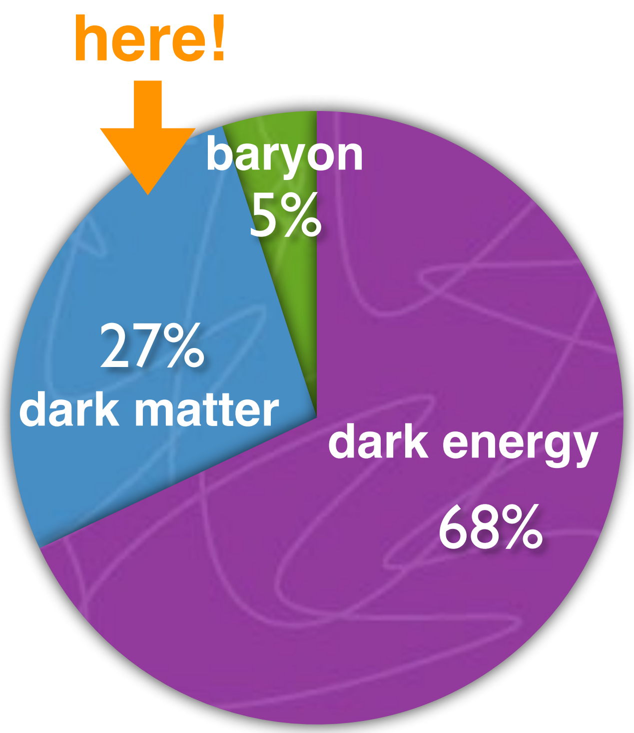
We know several properties, but do not know the identity

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

- coincidence?





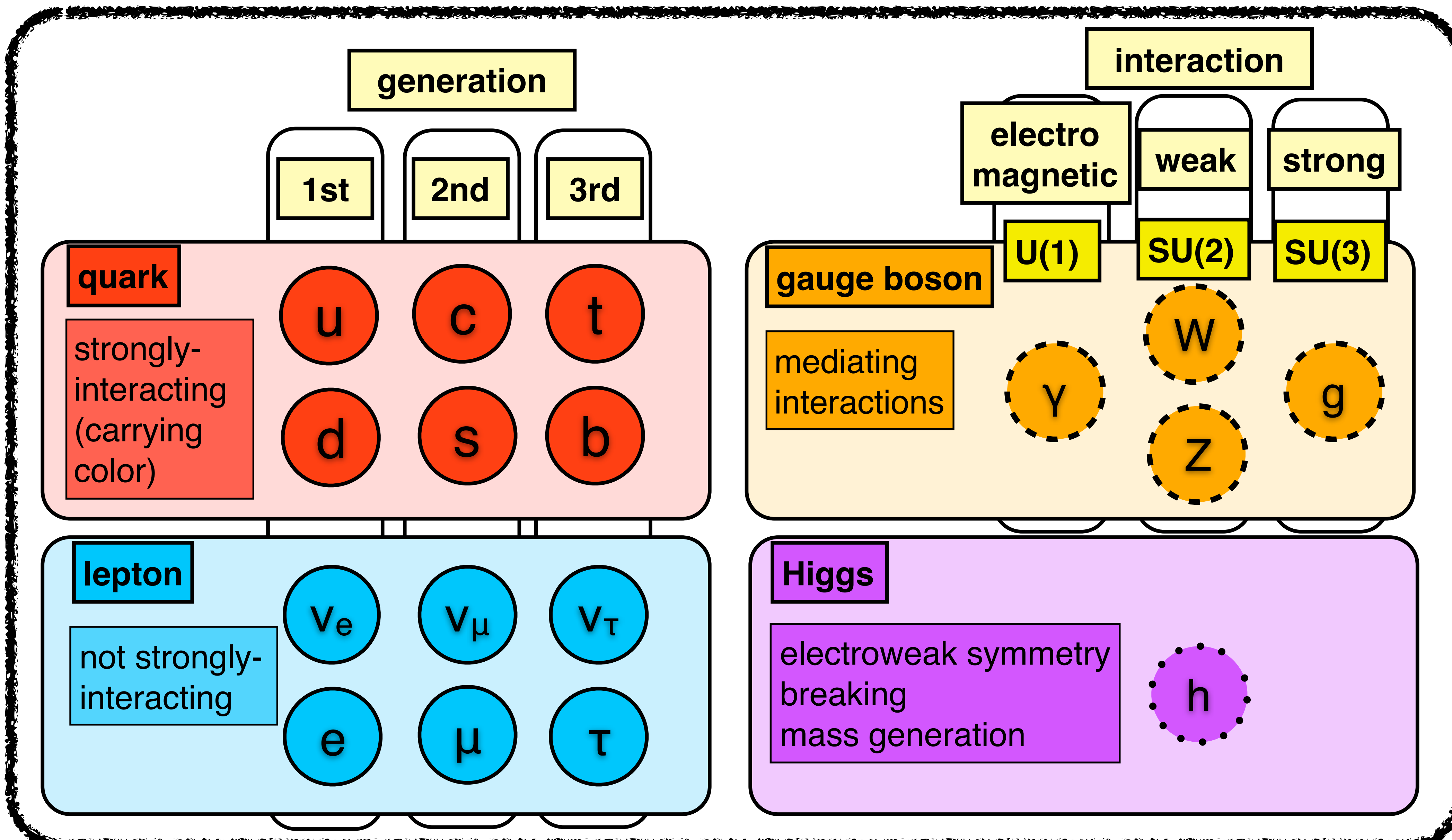


- cosmic microwave background (CMB) anisotropies

Candidate in the SM?

Standard model (SM) of particle physics

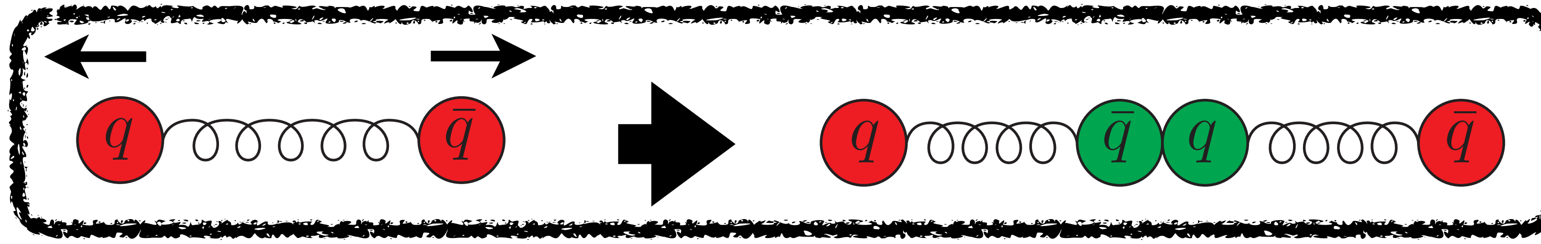
- language: relativistic quantum field theory
- dynamics: spontaneously broken $SU(3) \times SU(2) \times U(1)$ chiral gauge theory

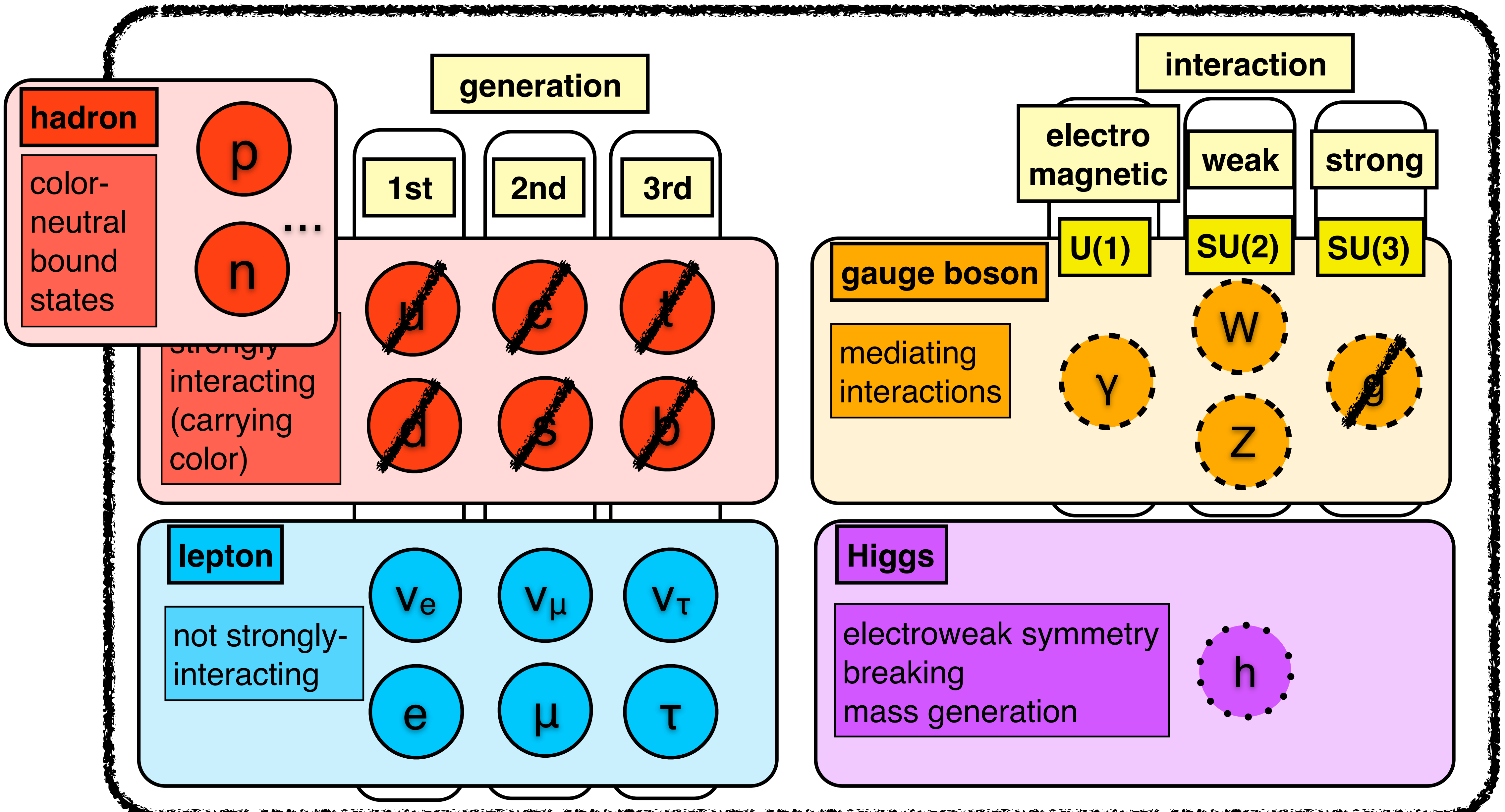


Candidate in the SM?

Color $SU(3)$: asymptotic freedom

- only color-neutral bound states appear as a free particle



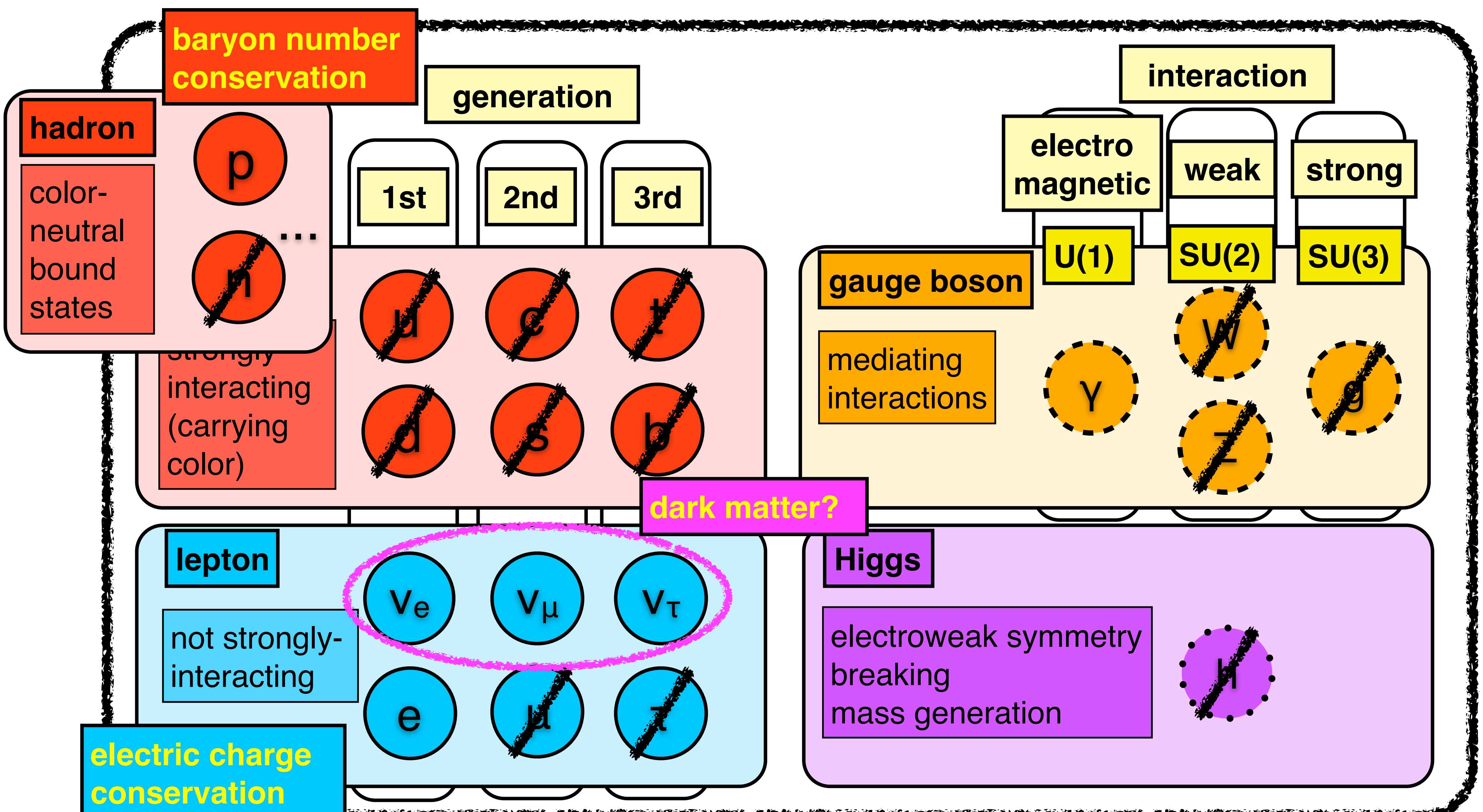


Candidate in the SM?

Heavy particle decays into lighter particles

- conservation law ↔ symmetry

  ✳ accidental symmetry: $U(1)_B \quad \Lambda_{\rm QCD}/M_* \ll 1$



Neutrino DM

Neutrinos ν_e ν_μ ν_τ are massless in the SM

$$\rho_\nu \propto 1/a^4$$

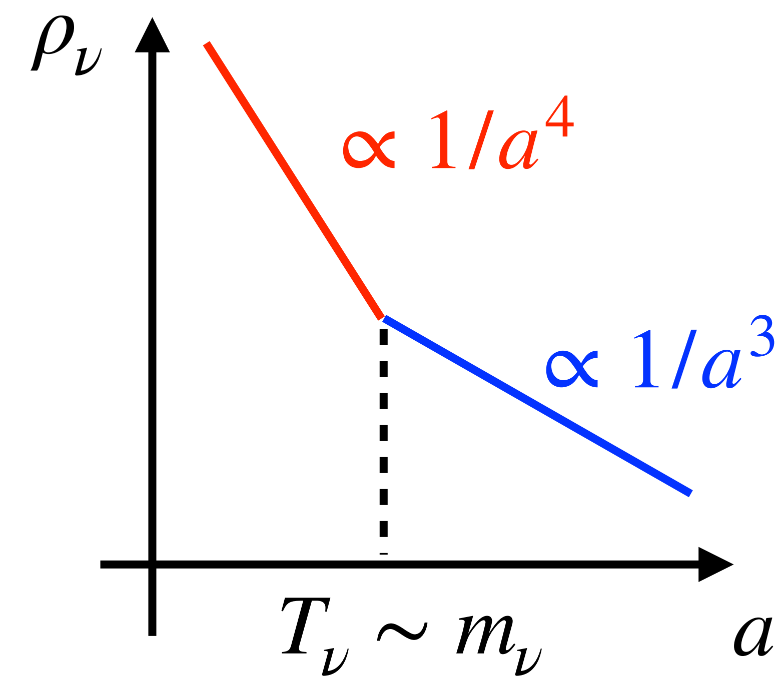
c.f. matter: $\rho_{\rm mat} \propto 1/a^3$ $a(t)$: scale factor of the Universe

Discovery of neutrino oscillation - Nobel prize 2015

→ neutrinos have a tiny mass

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{94\,\mathrm{eV}} \Rightarrow \sum m_\nu = 10\,\mathrm{eV}$$

$$\Omega_{\rm dm} h^2 \simeq 0.12$$



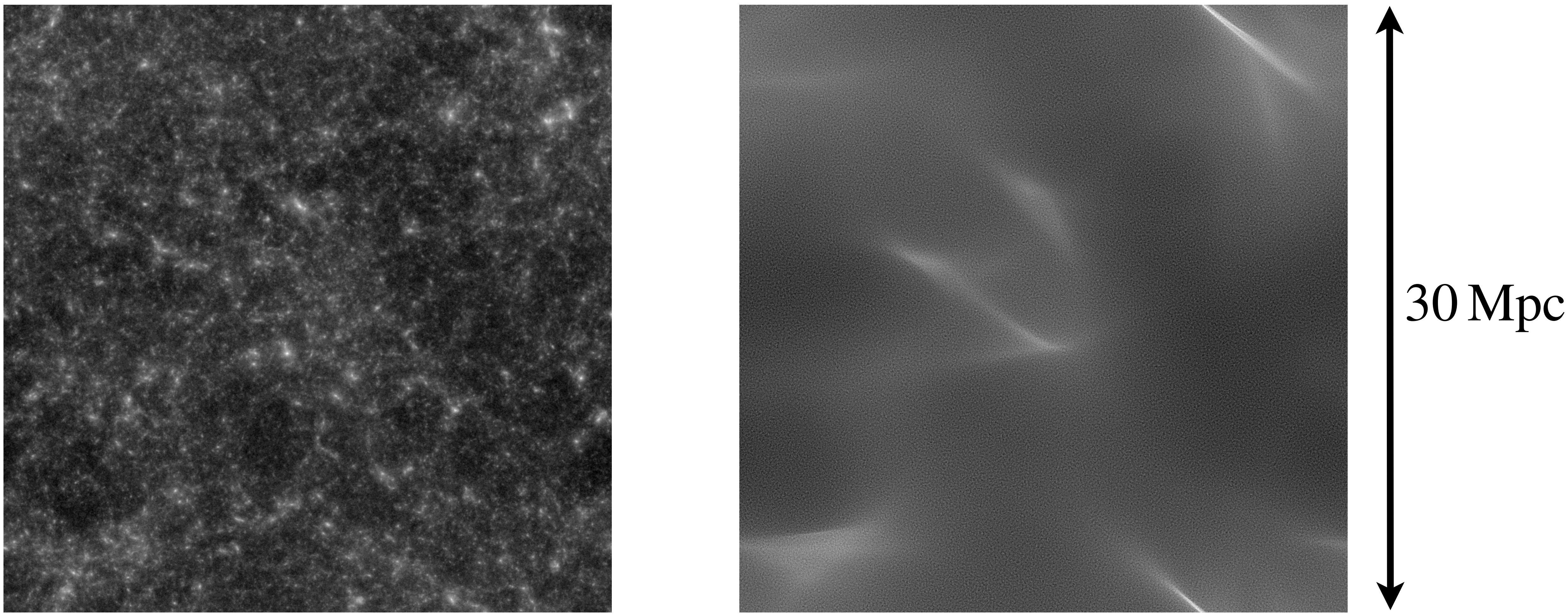
Neutrino DM becomes non-relativistic at $1/a \simeq 60000$

- corresponding size of the Universe: $5\,\mathrm{Mpc}$

Neutrino DM

Free-streaming of neutrino DM smears out the density contrast below $\sim 10\,\mathrm{Mpc}$

c.f. galaxy cluster size: $\sim 100\,\mathrm{kpc}$ galaxy: $\sim 10\,\mathrm{kpc}$



- cold dark matter
- hot dark matter

SM neutrinos are too hot to account for the whole DM

→ beyond SM physics

Pre-LHC: WIMP miracle

Naturalness

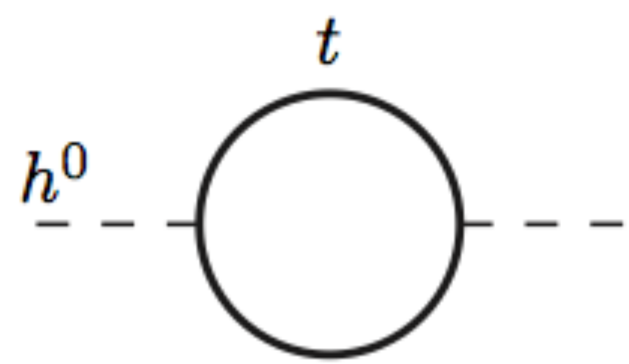
Higgs mass squared is very UV sensitive

not protected by any symmetry

- quantum correction shows quadratic divergence

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

$\Delta(m_{h^0}^2) =$



$\sim \dfrac{y_t^2}{(4\pi)^2}\Lambda^2$

Λ : naive cutoff

- large mass squared from quartic coupling to a scalar field with a large VEV

$$\lambda_{H\Sigma} |H|^2 |\Sigma|^2 \qquad \langle \Sigma \rangle \sim 10^{16}\,\text{GeV}$$

What about fermion masses? chiral symmetry!

What about vacuum energy (cosmological constant)? homework!

WIMP

Naturalness ➡ Λ : electroweak scale

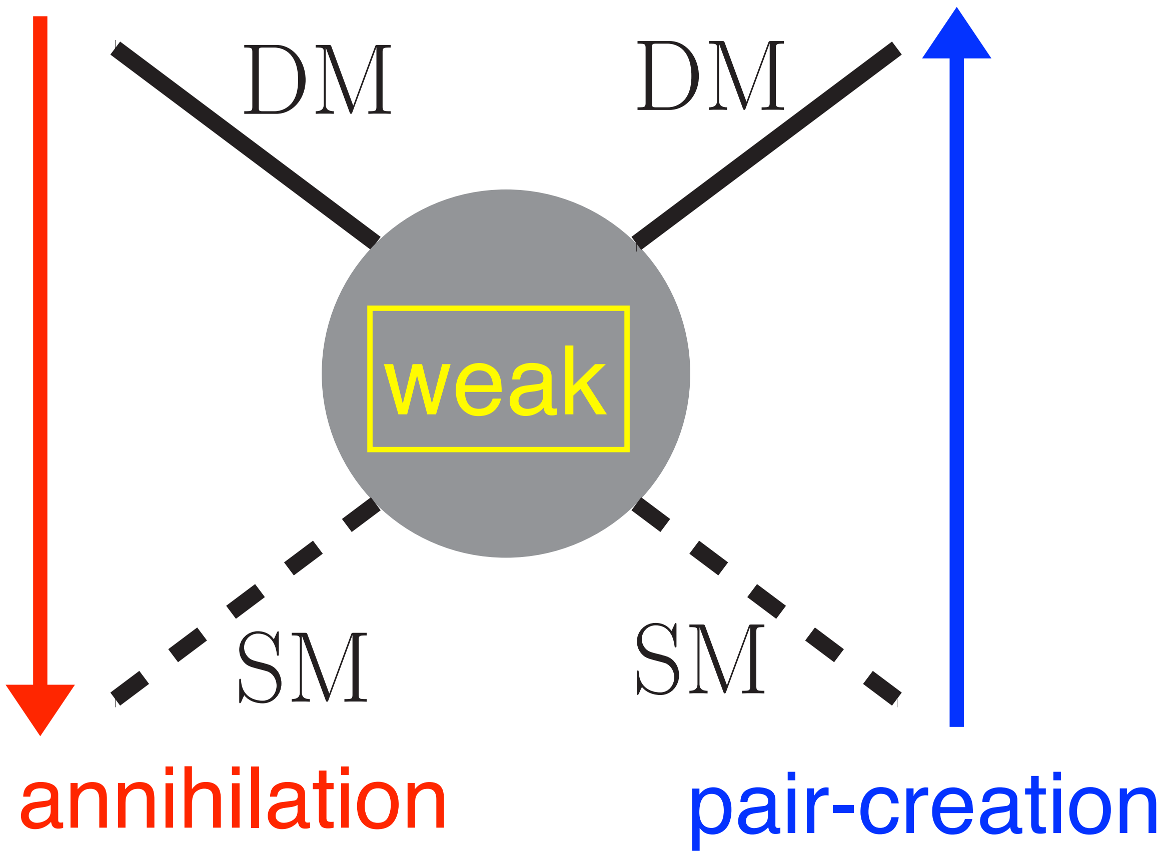
One expects that electoweak-scale new physics stabilizes the Higgs potential / explains the origin of the electroweak symmetry breaking

This new physics will provide a new particle with the electroweak-scale mass as a dark matter candidate

- stabilized by new $\mathbb{Z}_2$ symmetry

➡ Weakly interacting massive particle (WIMP)

WIMP

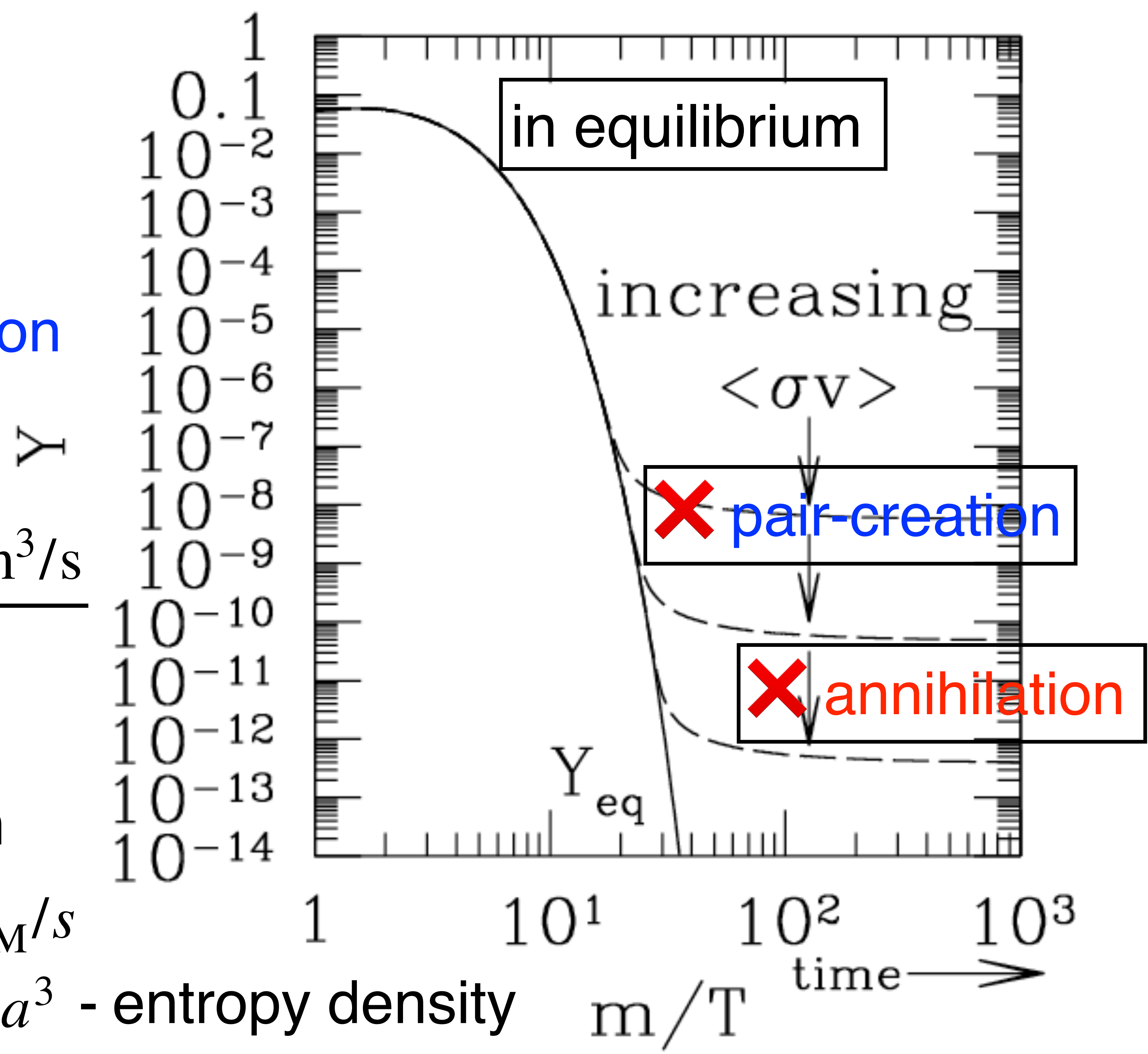


Thermal freeze-out

$$\Omega_{\rm WIMP}h^2 = 0.1 \times \frac{3\times 10^{-26}\,{\rm cm}^3/{\rm s}}{\langle \sigma_{\rm ann} v\rangle}$$

- only depend on the annihilation cross section

$\mathbb{Z}_2$ symmetry allows annihilation



$Y_{\rm DM} = n_{\rm DM}/s$

$s \propto 1/a^3$ - entropy density

WIMP miracle

Required annihilation cross section $\langle \sigma_{\rm ann} v \rangle \sim \dfrac{1}{(10^2\,{\rm TeV})^2}$

Naive WIMP annihilation cross section $\langle \sigma_{\rm ann} v \rangle \sim \dfrac{\alpha^2}{m_{\rm WIMP}^2}$

α : fine-structure constant ➡ $m_{\rm WIMP}$: electroweak scale!

More generically, from s-wave unitarity, $m_{\rm WIMP} \lesssim 340\,{\rm TeV}$

Griest, and Kamionkowsky, PRL, 1990

Electroweak-scale new physics

- naturalness
- DM candidate (WIMP)

Electro-weak scale SUSY

Theory is invariant under boson ↔ fermion

Theoretical properties

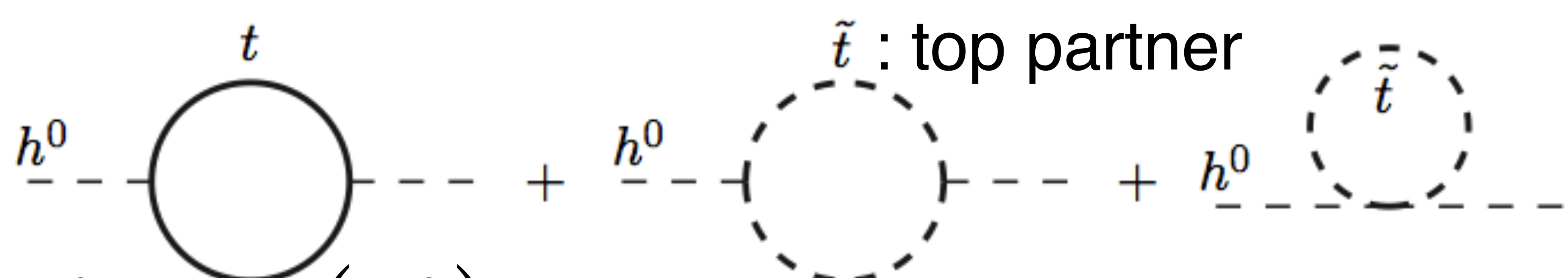
- non-trivially extend space-time (Poincaré) symmetry
- control quantum corrections through chiral symmetry

Minimal supersymmetric standard model (MSSM)

- SUSY breaking → electroweak symmetry breaking

$\tilde{t}$: top partner

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

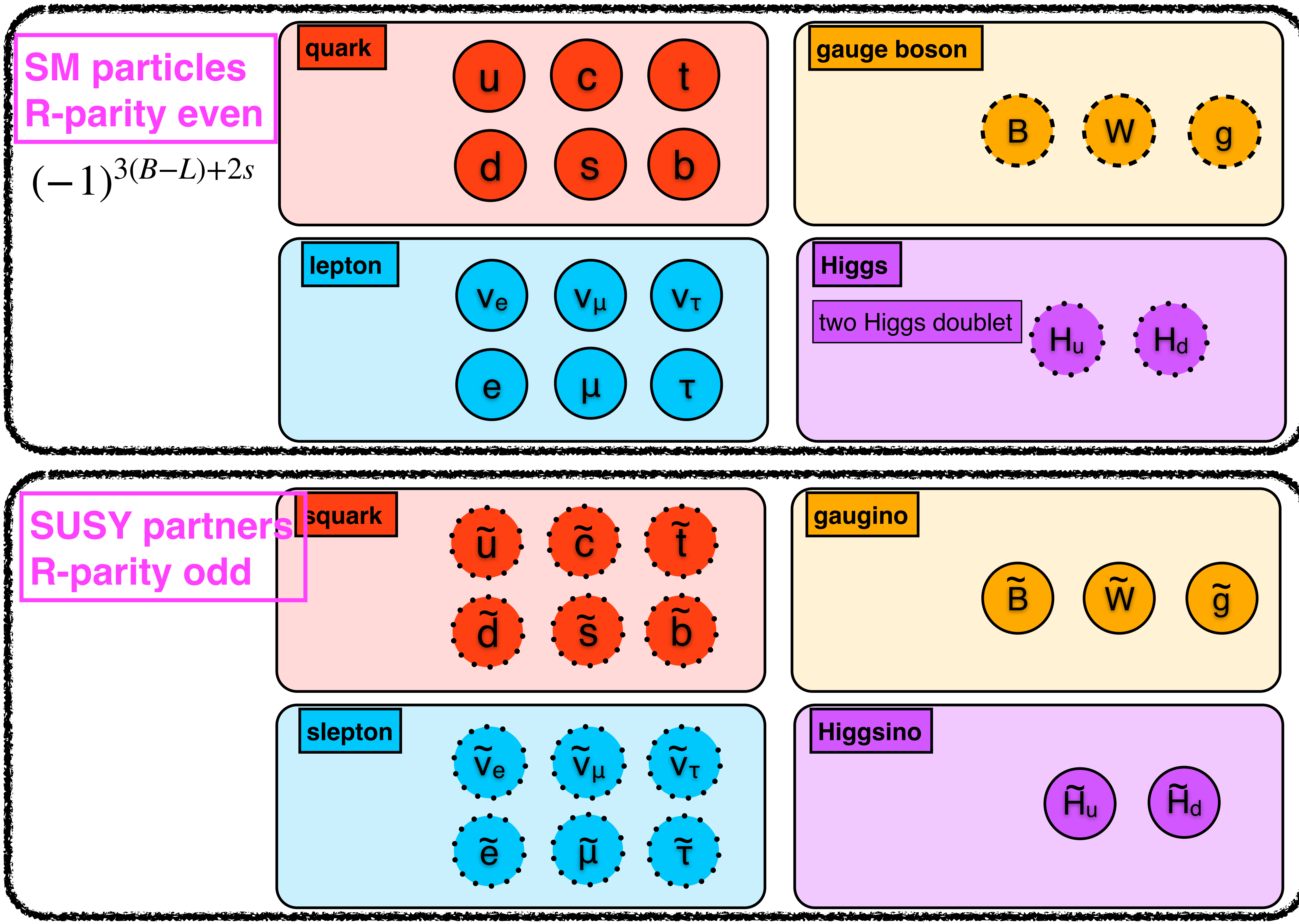


$$\sim \frac{y_t^2}{(4\pi)^2} m_{\tilde{t}}^2 \ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

➡ electroweak-scale $m_{\tilde{t}}$

naturalness

MSSM and R-parity



DM in the MSSM

Lightest supersymmetric particle (LSP)

- stable due to R-parity

Neutralino LSP: bino $\tilde{B}$, wino $\tilde{W}$, Higgsinos $\tilde{H}_u$ $\tilde{H}_d$

- DM (WIMP) candidates
- correct relic abundance ↔ specific SUSY spectrum

✳ special considerations are sometimes needed

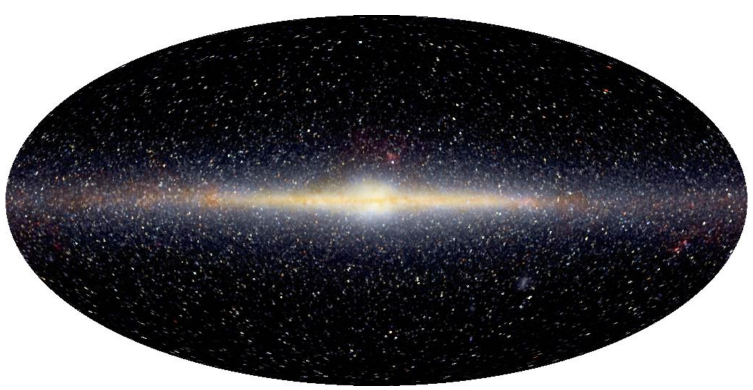
- co-annihilation
- forbidden
- resonant Griest, and Seckel, PRD, 1999
- Sommerfeld enhancement Hisano, Matsumoto, Nagai, Saito, and Senami, PLB, 2007
- bound-state formation Harling, and Petraki, JCAP, 2014

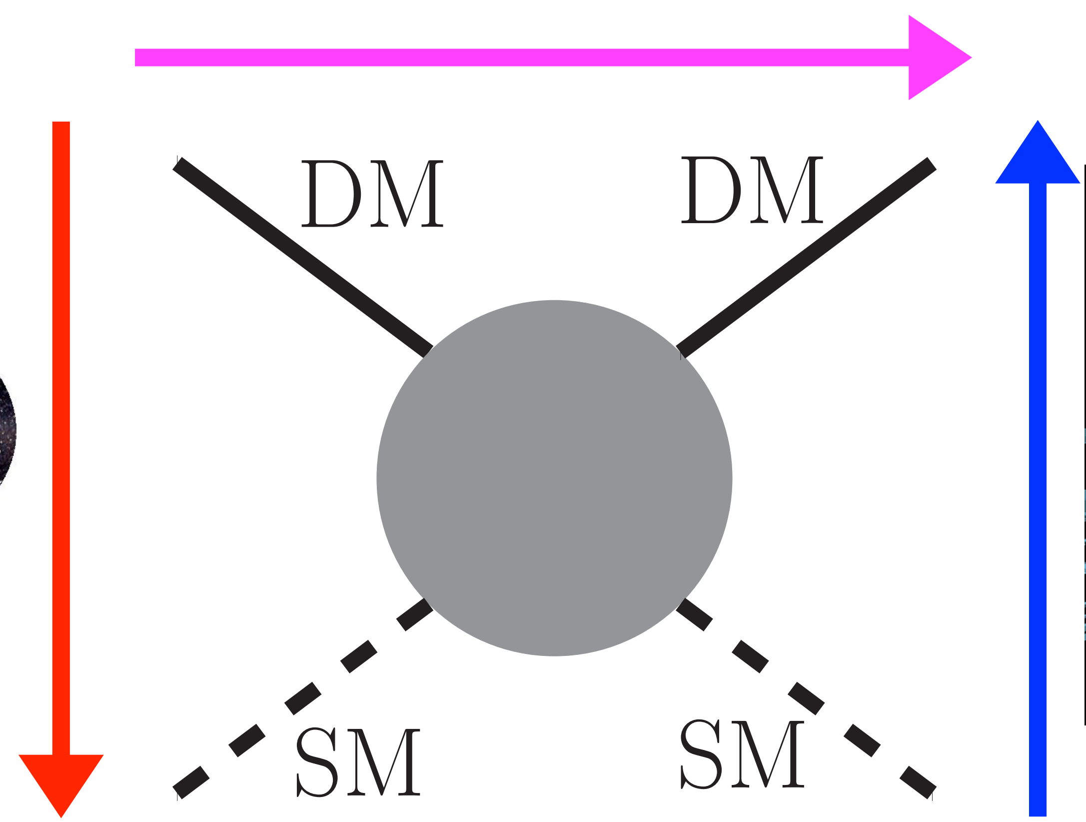
✳ sneutrinos $\tilde{\nu}_e$, $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$ are a good DM candidate at first sight but excluded by direct detection experiments (below)

WIMP search

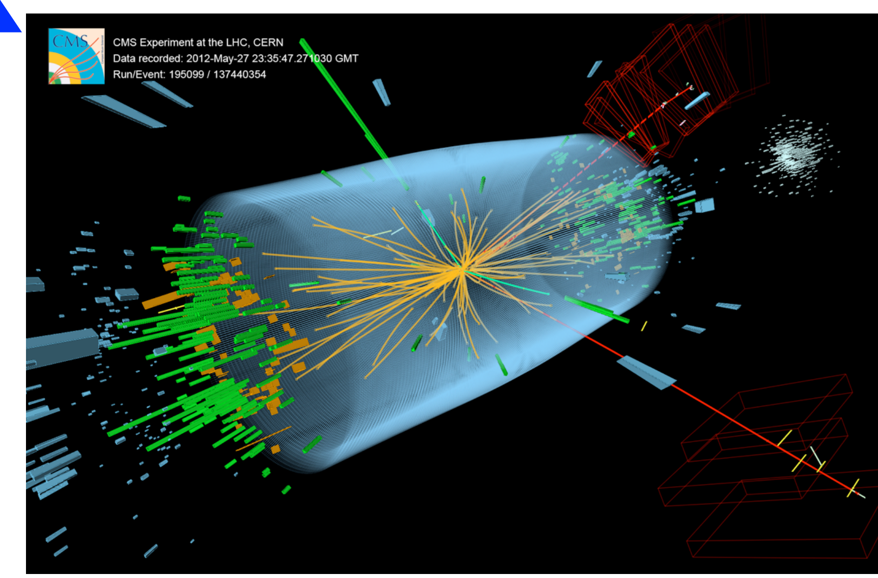
- direct detection

- indirect detection



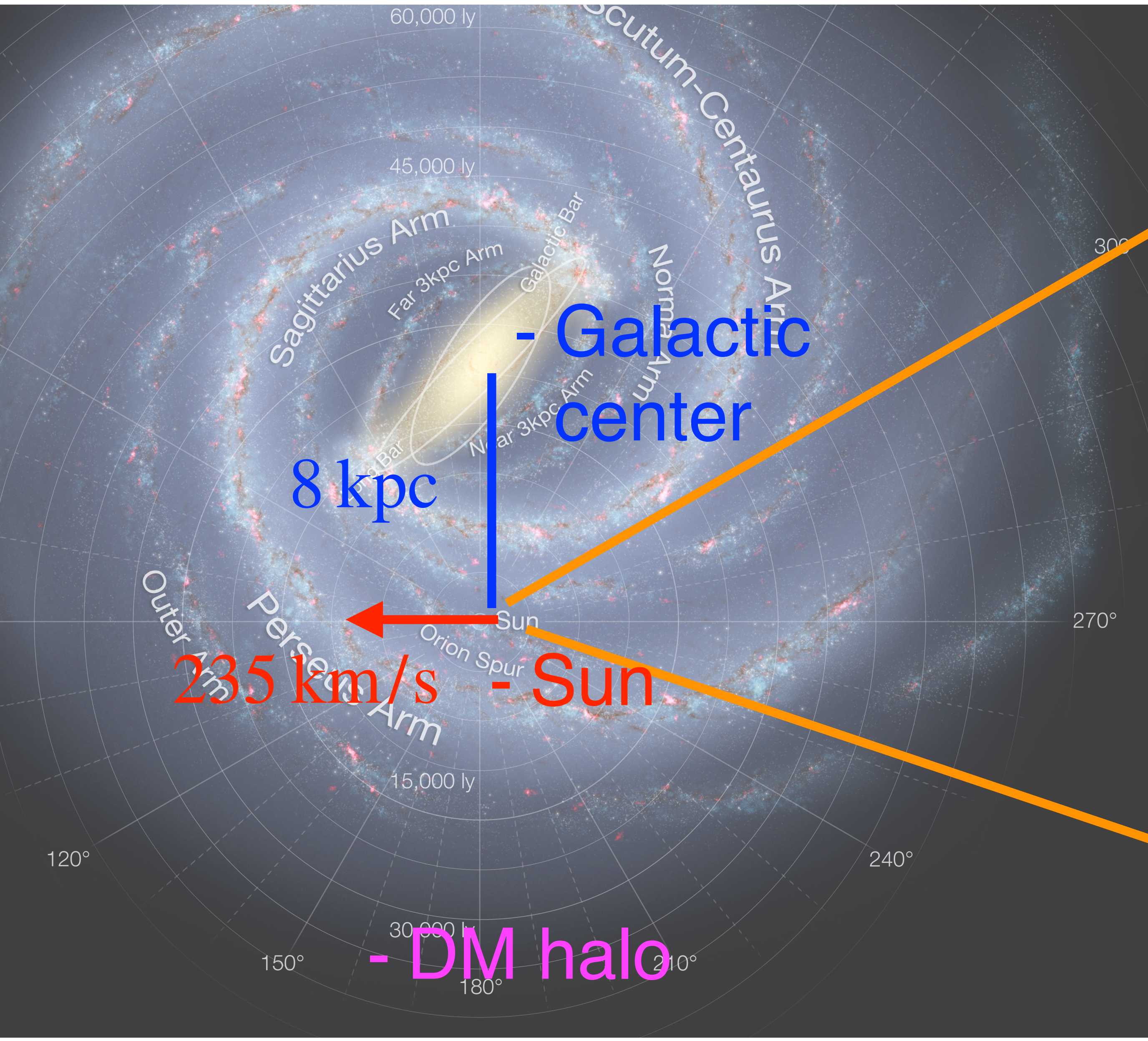


- collider

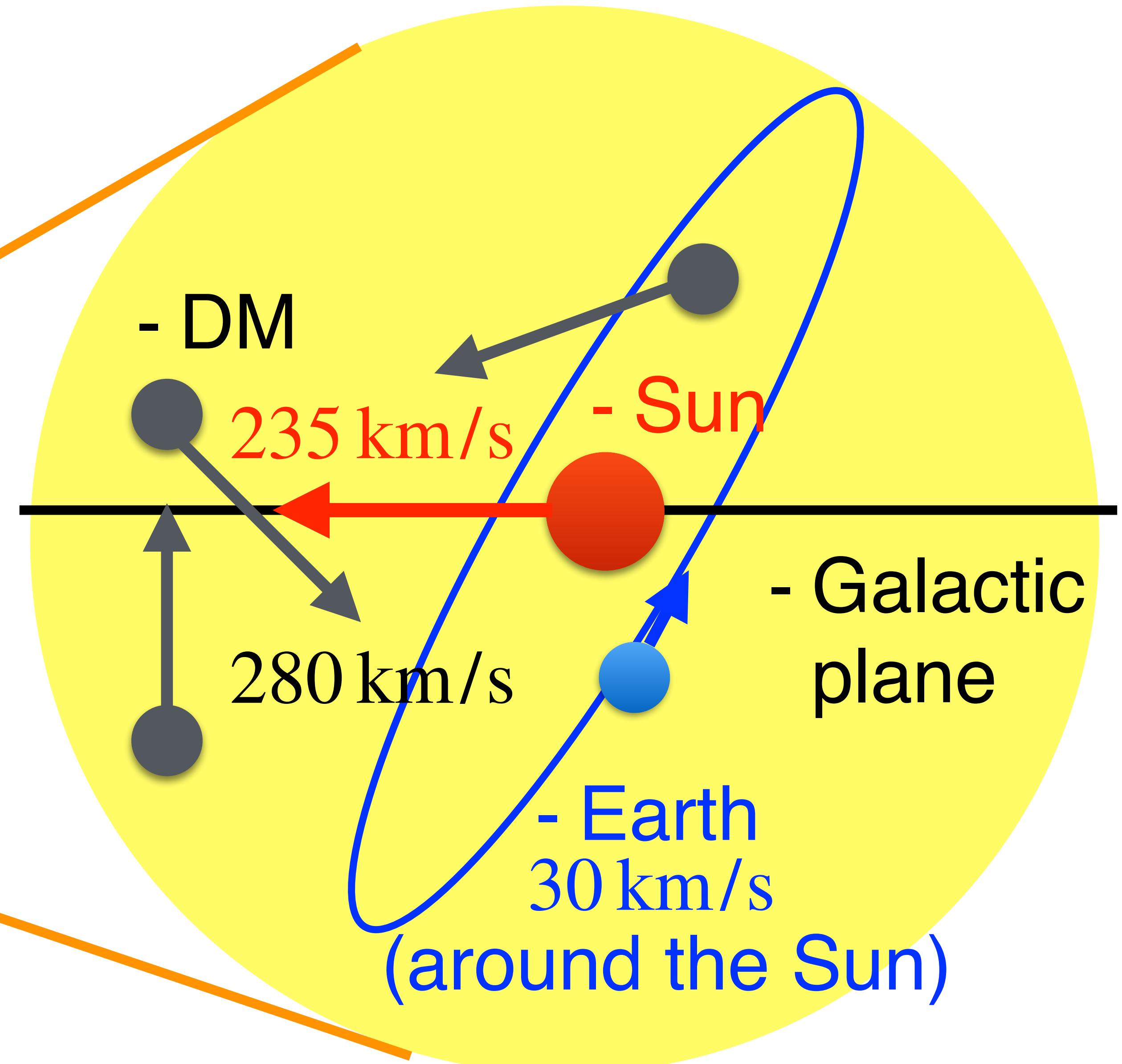


Direct detection

- face-on view of MW



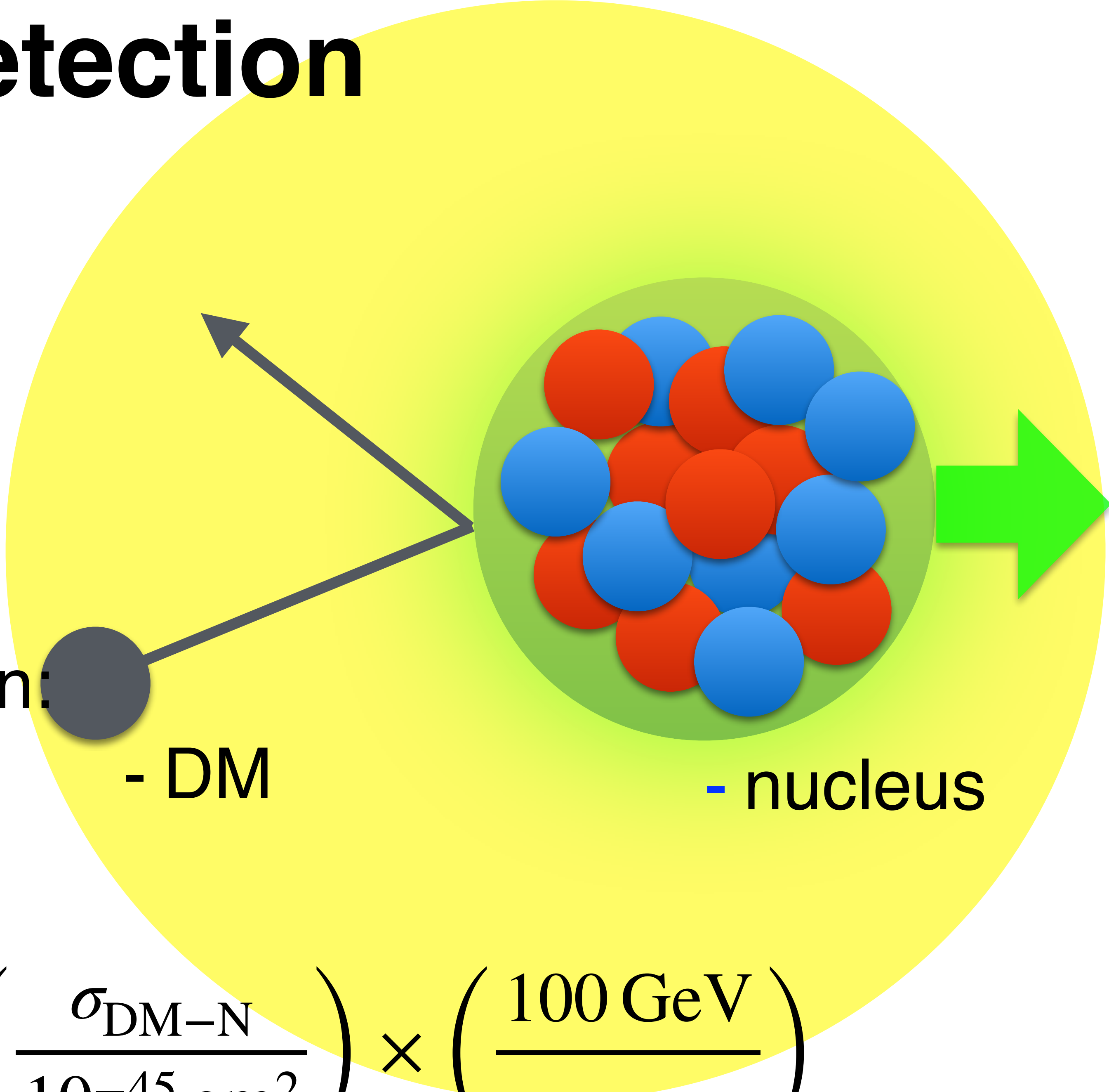
- edge-on view



Solar system moves around the Galactic plane
↔ DM wind blows to the Earth

Direct detection

DM scattering with a nucleus



DM number density around the Sun:

$$n_{\rm DM} \sim 3\times 10^{-3}\,/{\rm cm}^3 \times \left(\frac{100\,{\rm GeV}}{m_{\rm DM}}\right)$$

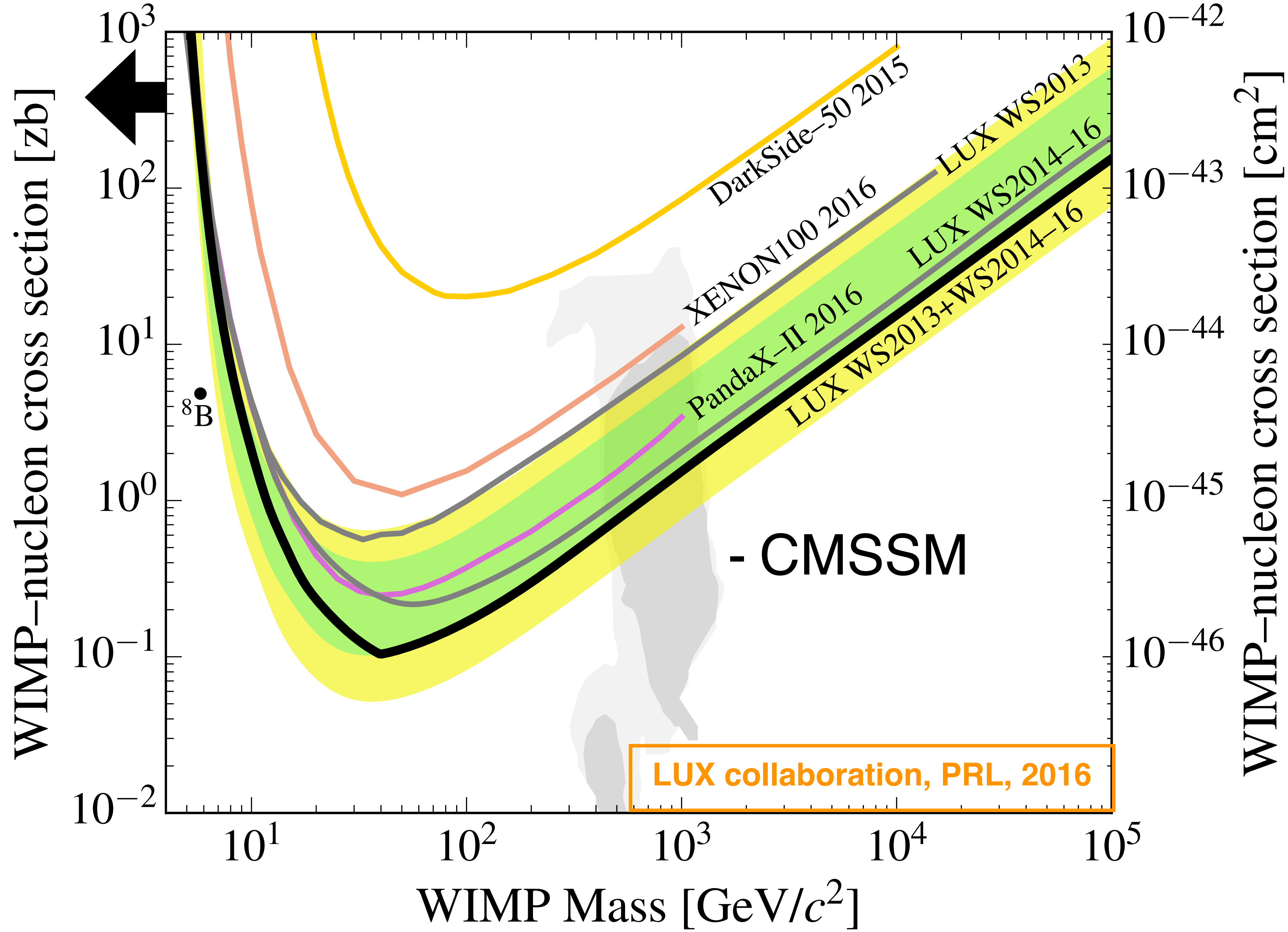
Low event rate: $\sim 0.3\,/{\rm kg}/{\rm year} \times \left(\frac{\sigma_{\rm DM-N}}{10^{-45}\,{\rm cm}^2}\right) \times \left(\frac{100\,{\rm GeV}}{m_{\rm DM}}\right)$

Small recoil energy: $\sim 1\,{\rm keV} \times \left(\frac{m_{\rm DM}}{100\,{\rm GeV}}\right)\left(\frac{v}{200\,{\rm km/s}}\right)^2$

➡ Locate a high-sensitivity detector in a low-background environment such as a mine

Direct detection

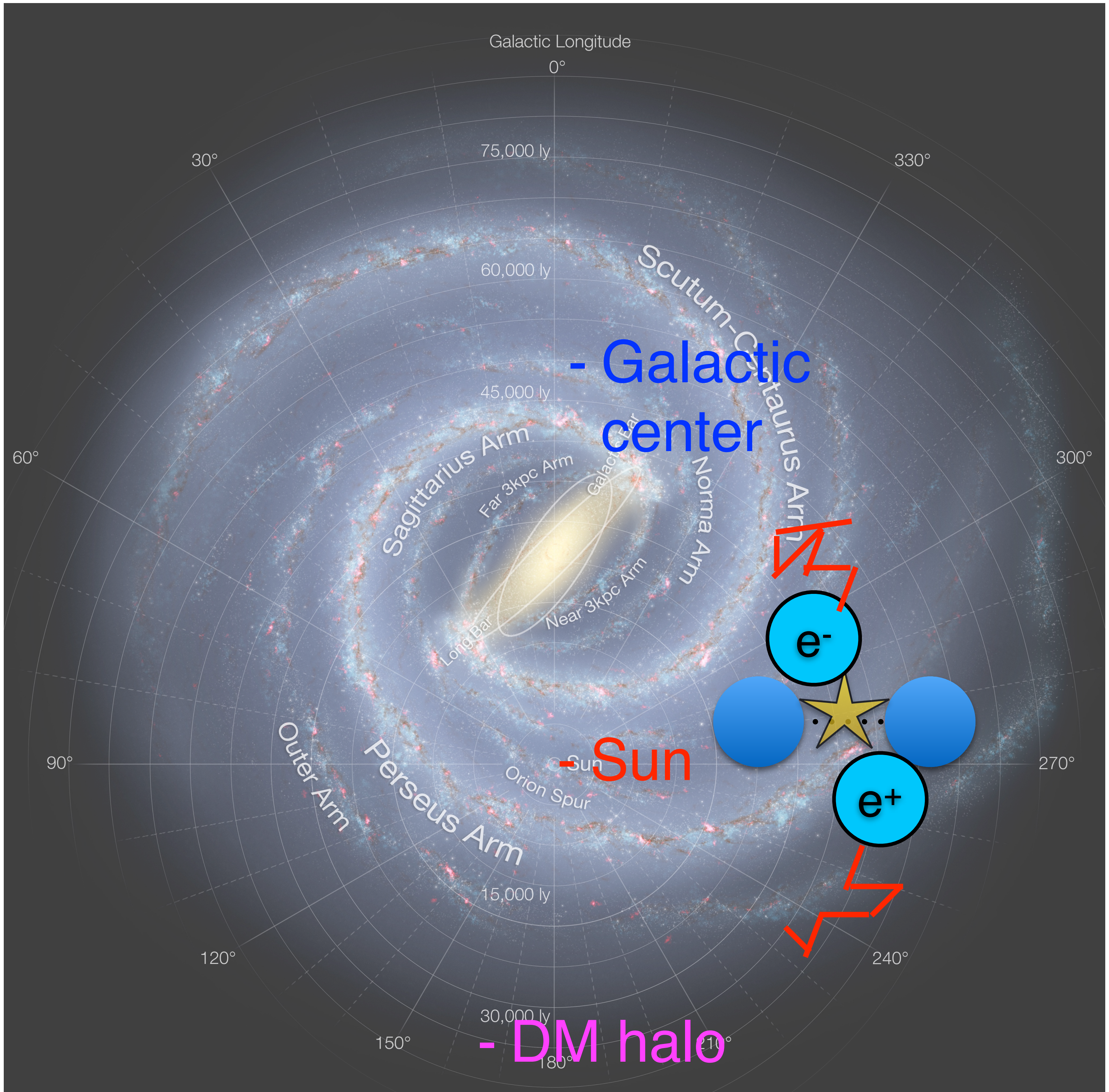
- too small recoil energy



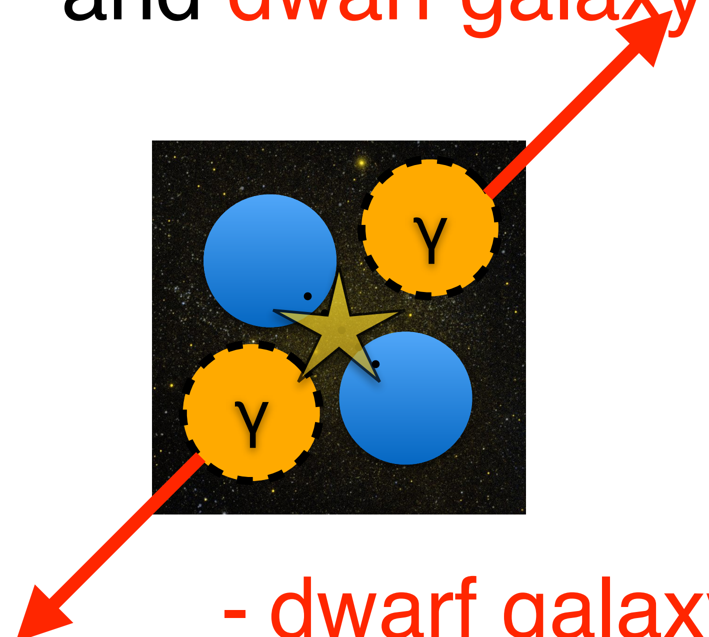
Null detections → tight constraints (covering part of the SUSY parameter space)

Indirect detection

DM annihilation in the late-time Universe



Target: high-density region such as Galactic center and dwarf galaxy

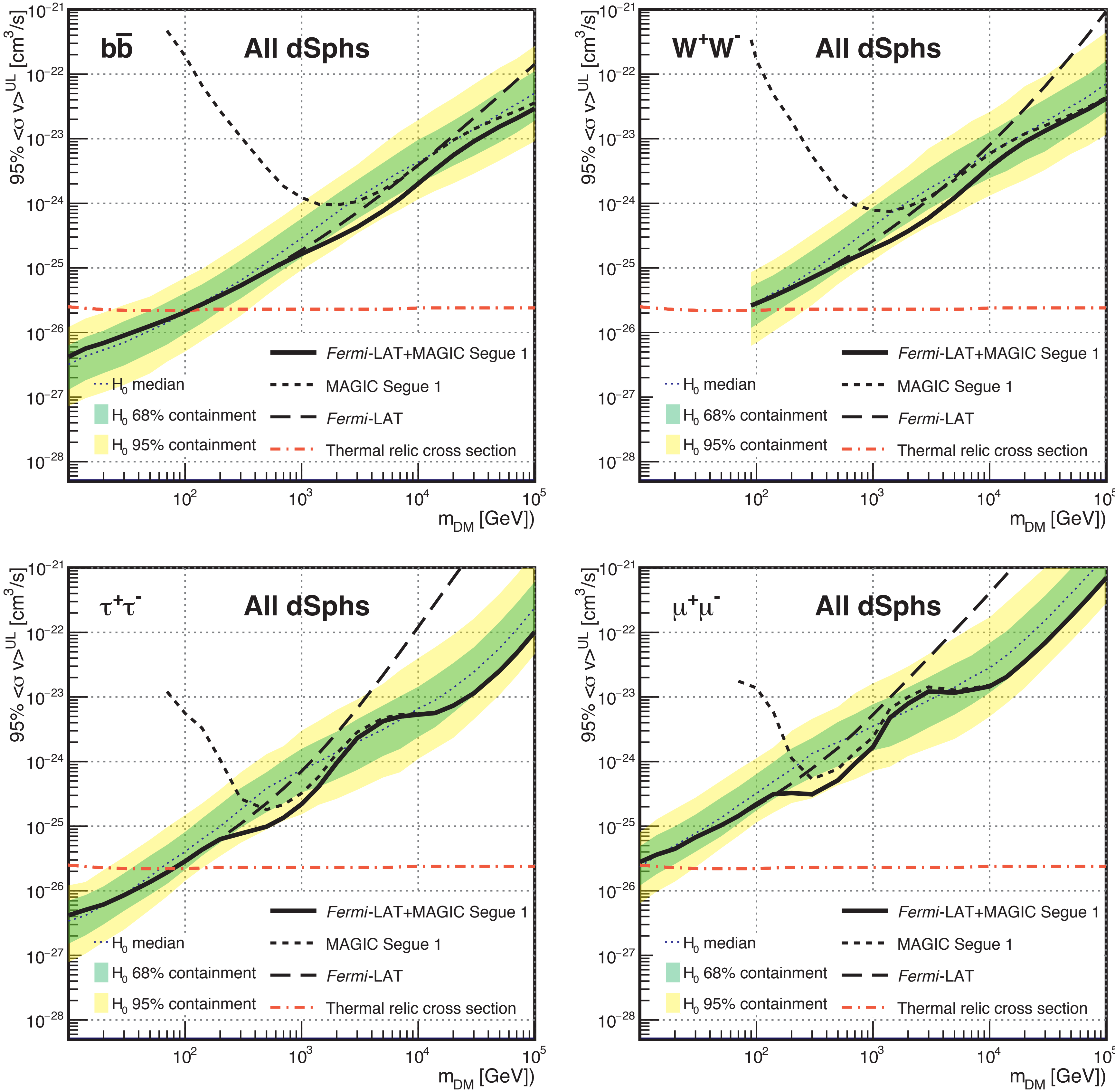


- dwarf galaxy

- diffusion of charged particles → only local region contributes

Indirect detection

annihilation cross section



DM mass

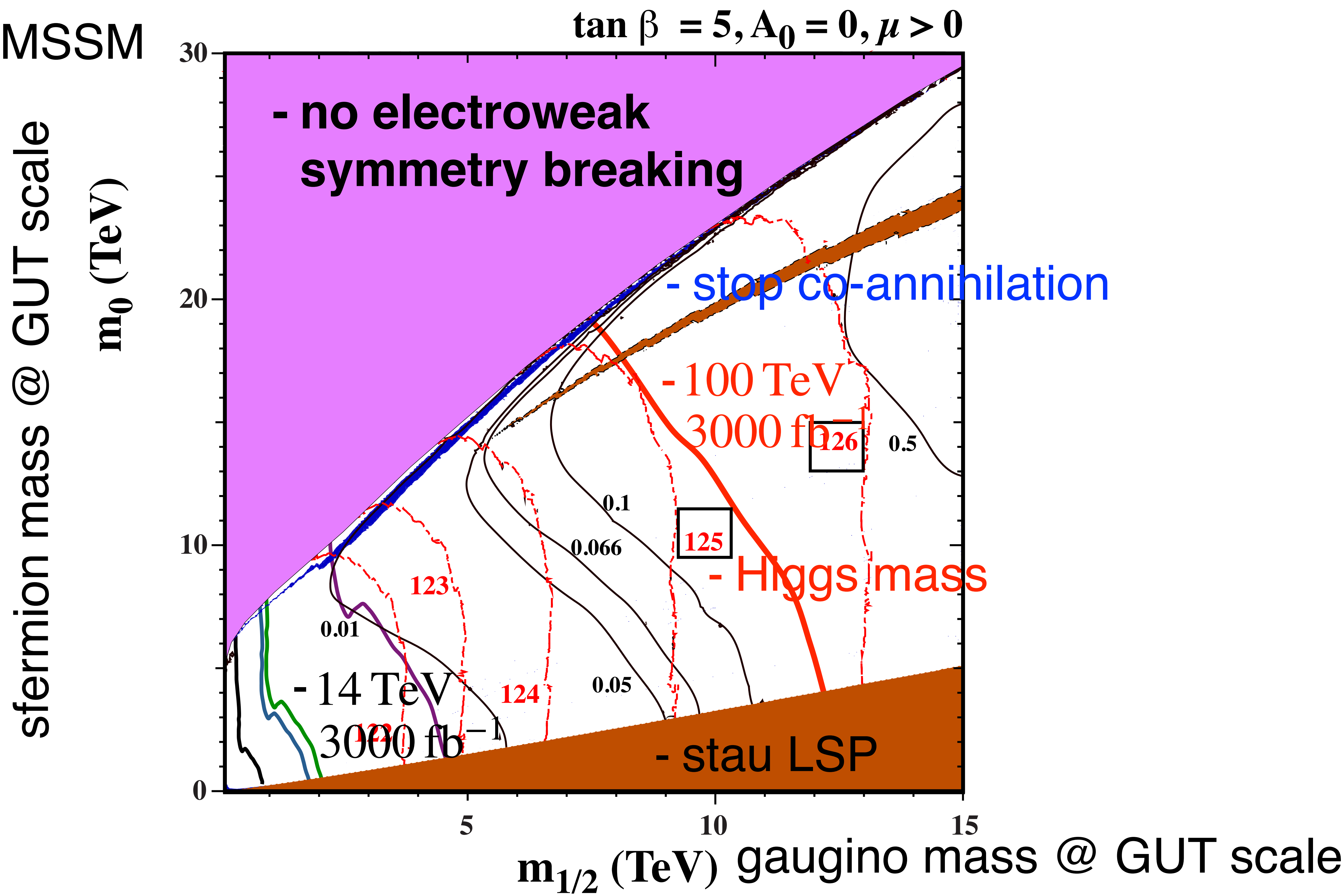
- canonical cross section for a correct relic abundance

✴ if no velocity dependence

Magic and Fermi-LAT Collaborations, JCAP, 2016

Collider

CMSSM



Ellis, Evans, Mustafayev, Nagata, Olive, Eur. Phys. J., 2016

Sparticle masses have been pushed up to ~TeV

Post-LHC: brainstorming

No naturalness so far…

LHC discovery of $125\,\mathrm{GeV}$ Higgs and null-detection of top partners

- something wrong in the hierarchy problem and postulated solutions (including but not only electroweak-scale SUSY)

WIMP is no more as a miracle as we expected…

- top-down: new theoretical reasoning for WIMP?

- bottom-up: structure formation of the Universe?

Grand unification

$U(1)_Y$ charge is quantized in multiples of $1/6$

⬍ miraculously free from quantum anomaly

Abelian group can have any charge

Embed the SM gauge group
in a non-Abelian gauge group

$SU(5) \supset SU(3) \times SU(2) \times U(1)$

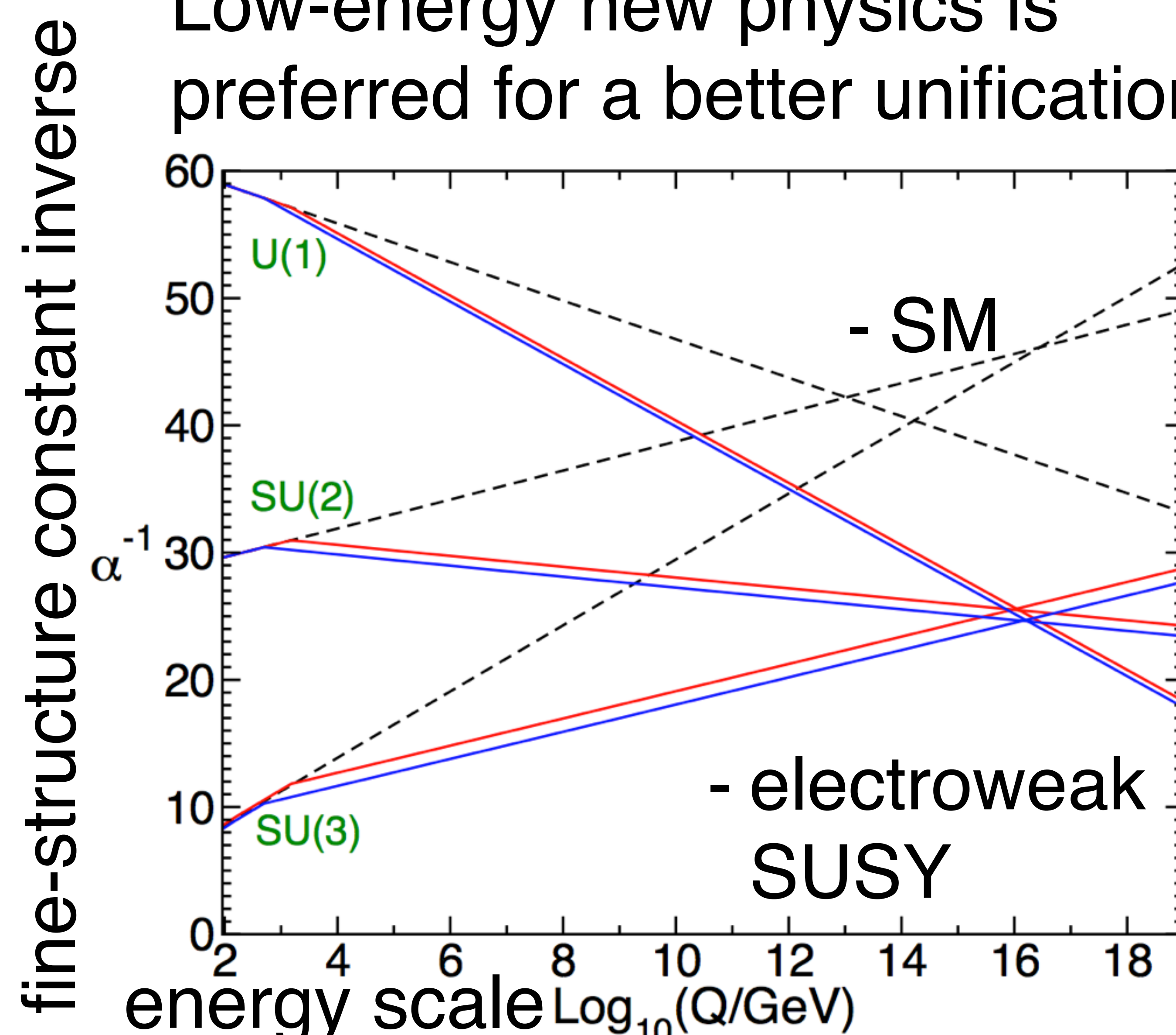
$\mathrm{diag}(-1/3, -1/3, -1/3, 1/2, 1/2) \times \sqrt{3/5}$

$\mathbf{10} : (Q(1/6), \overline{u}(-2/3), \overline{e}(1))$

$\overline{\mathbf{5}} : (\overline{d}(1/3), \hat{L}(-1/2))$

$\mathbf{5}_H : (H_C(-1/3), H_u(1/2))$

Low-energy new physics is
preferred for a better unification



Mini-split supersymmetry

Arkani-Hamed and Dimopoulos, JHEP, 2005 | Giudice and Romanino, NPB, 2004 | Wells, PRD, 2005 ...

Mini-split SUSY: pragmatic SUSY mass spectrum

- sfermions, heavy Higgses, gravitino $> 100\,\mathrm{TeV}$
  - 125 GeV Higgs although the little hierarchy problem (electroweak scale v.s. SUSY breaking scale) unanswered
  - no experimental (e.g., flavor) or cosmological (e.g., gravitino) problem

- gauginos $\sim 1\,\mathrm{TeV}$; higgsino ~ ???: experimental window
  - provide a dark matter candidate
    - another WIMP miracle?
  - precise grand unification of gauge couplings

Dark matter candidate

gravitino $\sim 100\,\mathrm{TeV}$, gauginos $\sim 1\,\mathrm{TeV}$ - anomaly mediation

→ (likely) wino (or higgsino) dark matter

Randall and Sundrum, NPB, 1999

Giudice, Luty, Murayama, and Rattazzi, JHEP, 1998

Thermal pure wino dark matter

Ibe and Yanagida, PLB, 2012 **Ibe, Matsumoto and Yanagida, PRD, 2012** ...

higgsino $> 100\,\mathrm{TeV}$

neutralino (χ^0) and charginos ($\chi^\pm$) $\Delta m_\chi \simeq 160\,\mathrm{MeV}$

Ibe, Matsumoto, and Sato PLB, 2013 ...

perturbative annihilation $\chi^0\chi^0 \to W^+W^-$

+ co-annihilation

+ Sommerfeld enhancement

→ $\Omega_\chi h^2 = \Omega_{\rm dm} h^2$ for $m_\chi \simeq 3\,\mathrm{TeV}$

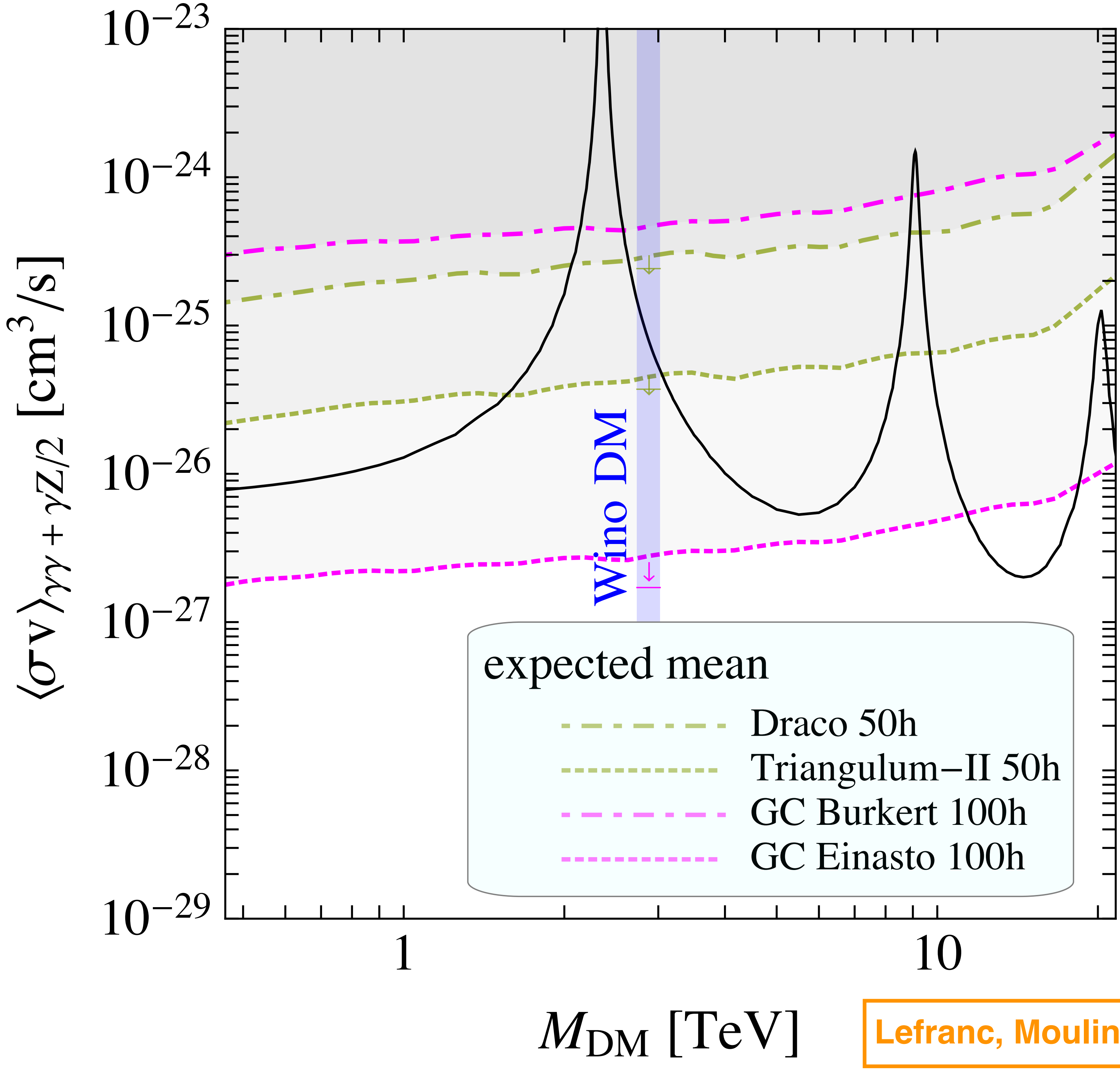
Hisano, Matsumoto, Nagai, Saito, and Senami, PLB, 2007 ...

- no free parameter left

- accompanied by slightly heavier charged component (EWIMP or electroweakino)

Indirect detection

CTA sensitivities



✴Galactic center has a large uncertainty in the DM profile

Lefranc, Moulin, Panci, Sala, and Silk, JCAP, 2016

No naturalness so far…

LHC discovery of $125\,\mathrm{GeV}$ Higgs and null-detection of top partners

- something wrong in the hierarchy problem and postulated solutions (including but not only electroweak-scale SUSY)

WIMP is no more as a miracle as we expected…

- top-down: new theoretical reasoning for WIMP?

- bottom-up: structure formation of the Universe?

Structure formation of the Universe

Structure formation is a good laboratory of dark matter

- provided the DM properties
- surveys are projected

Cold dark matter (CDM) hypothesis

⇕ - null thermal velocity; only gravitationally interacting

Particle physics candidates

- finite (sizable) thermal velocity; interacting in many ways

➡ Properties of dark matter are imprinted in the structure of the Universe as deviations from the CDM prediction

- imprints of dark matter properties are not fully understood
- for typical WIMPs, deviations appear at $\sim 1\,\mathrm{pc}$ scales
- impact indirect detection?

Small-scale structure

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

Bullock and Boylan-Kolchin, ARAA, 2018

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

Issues may indicate alternatives to CDM (WIMPs)

- beyond WIMP?

- Warm dark matter (WDM) $m \sim 1\,\mathrm{keV}$

- Self-interacting dark matter (SIDM) $\sigma/m \sim 1\,\mathrm{cm}^2/\mathrm{g}$

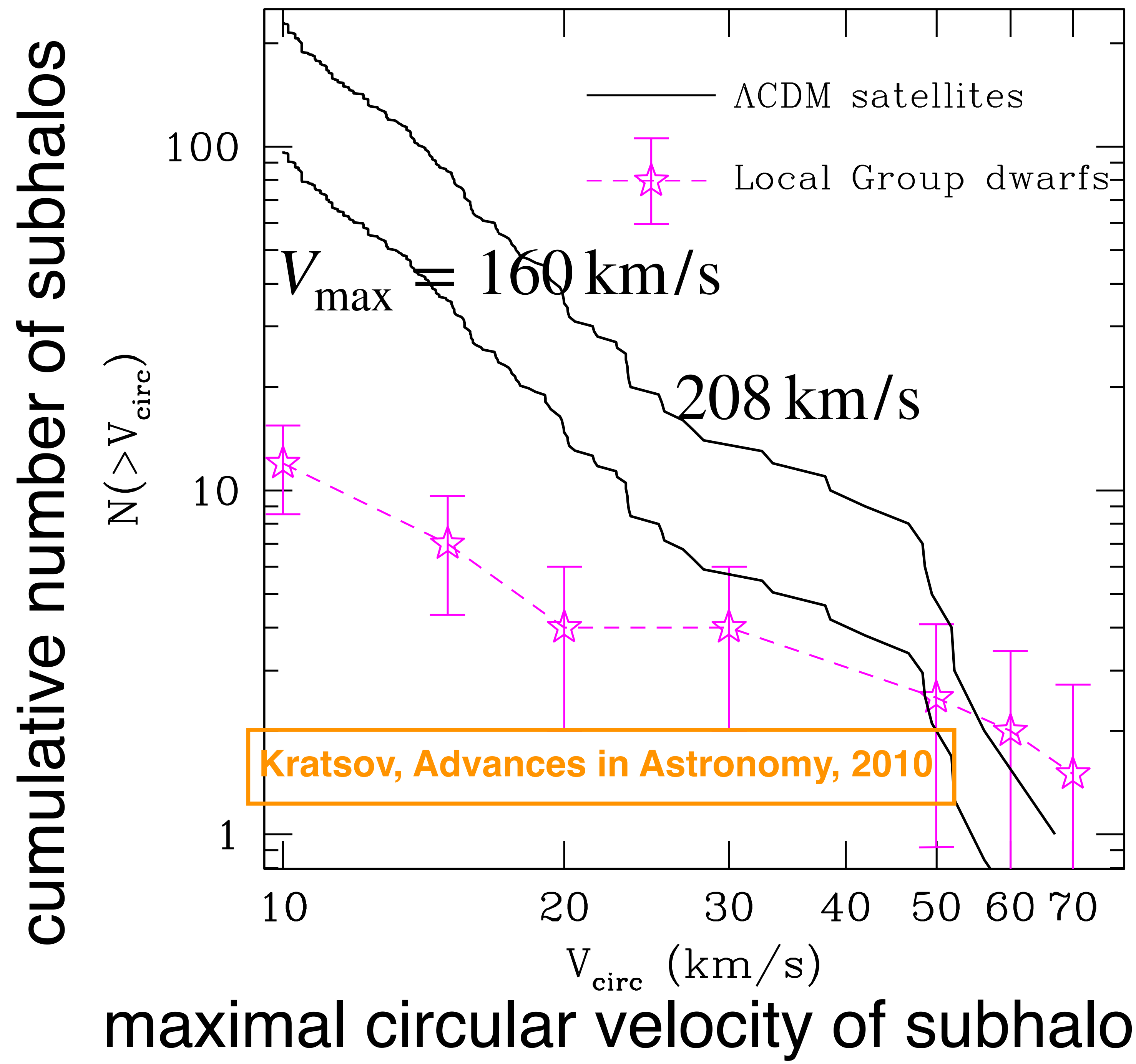
Missing satellite problem

N-body (DM-only) simulations in the ΛCDM model → a MW-size halo hosts a $\mathcal{O}(10)$ times larger number of subhalos than that of observed dwarf spheroidal galaxies

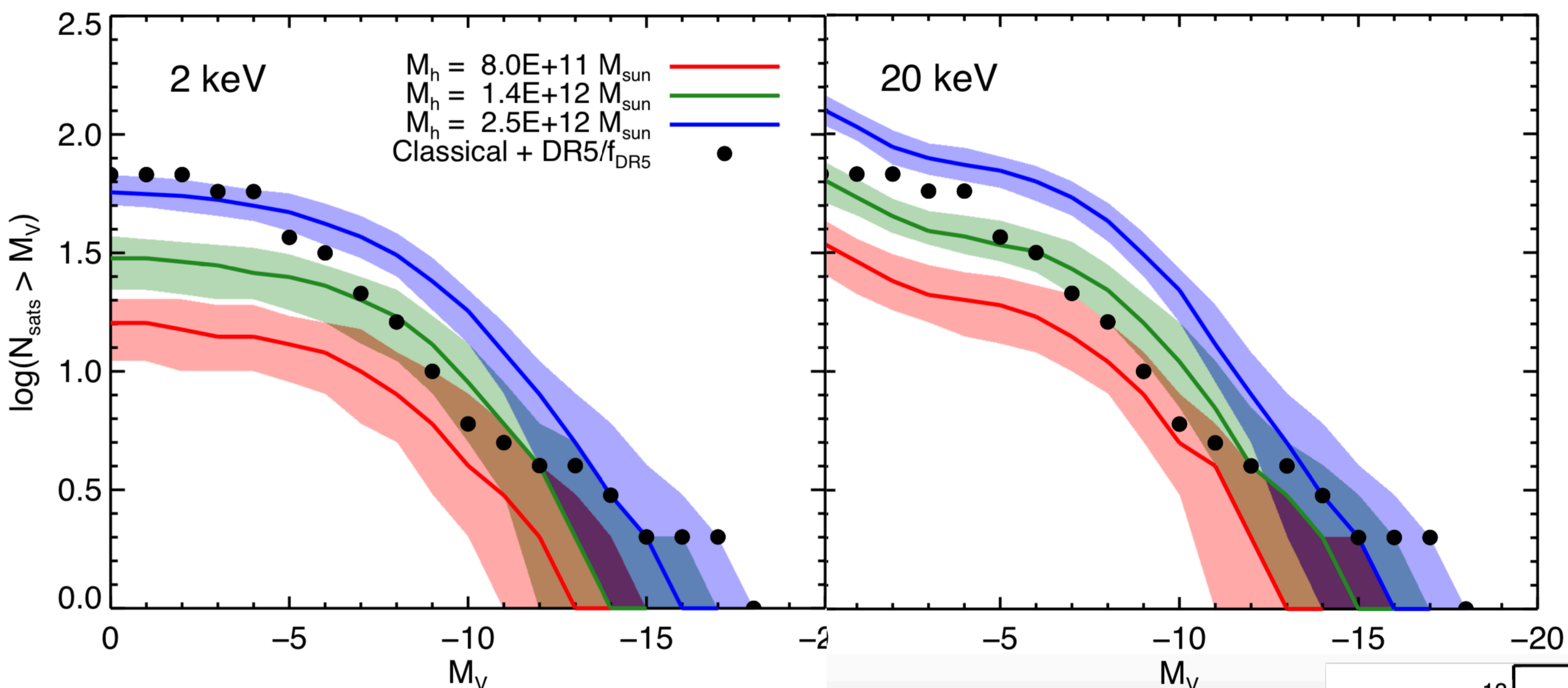
(maximum) circular velocity:

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

$$V_{\rm max} = \max_r \left(V_{\rm circ}(r)\right)$$



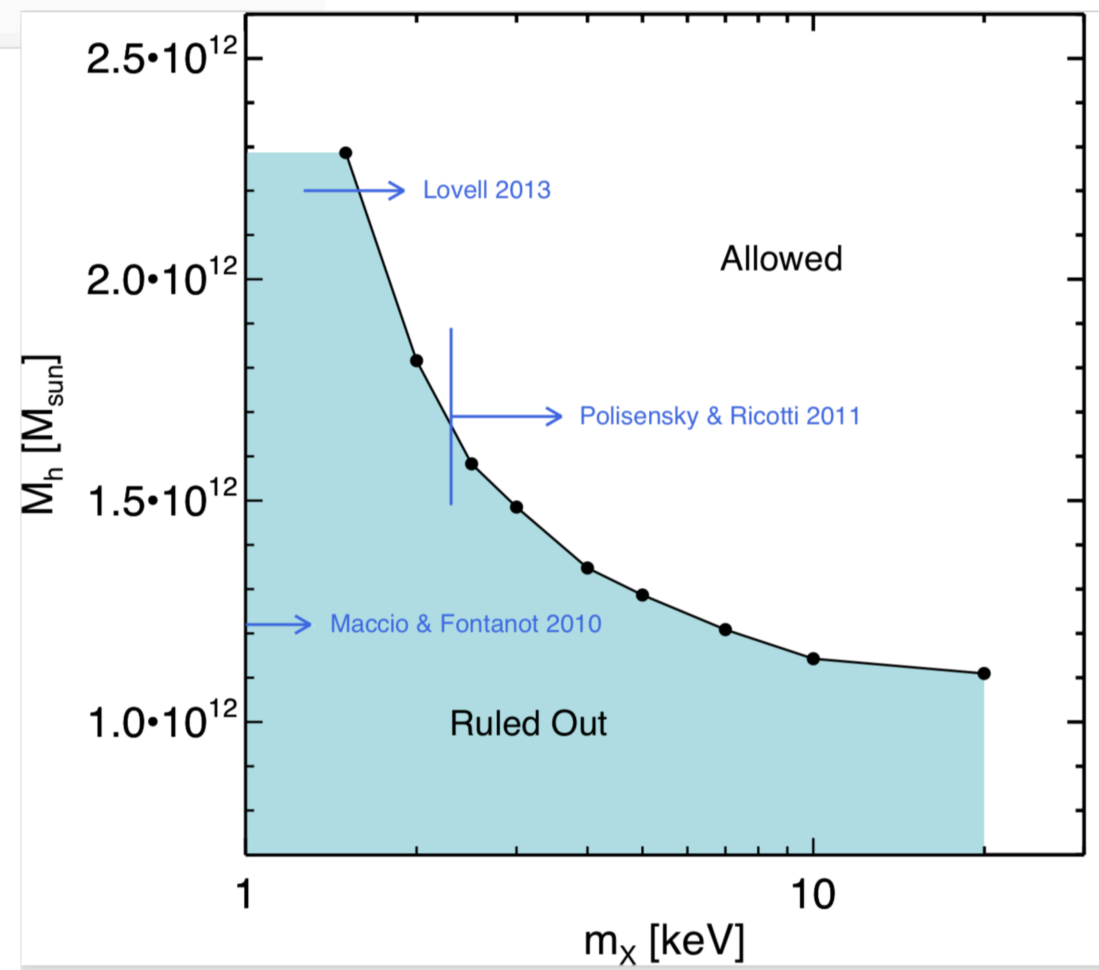
Missing satellite problem w/ WDM



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

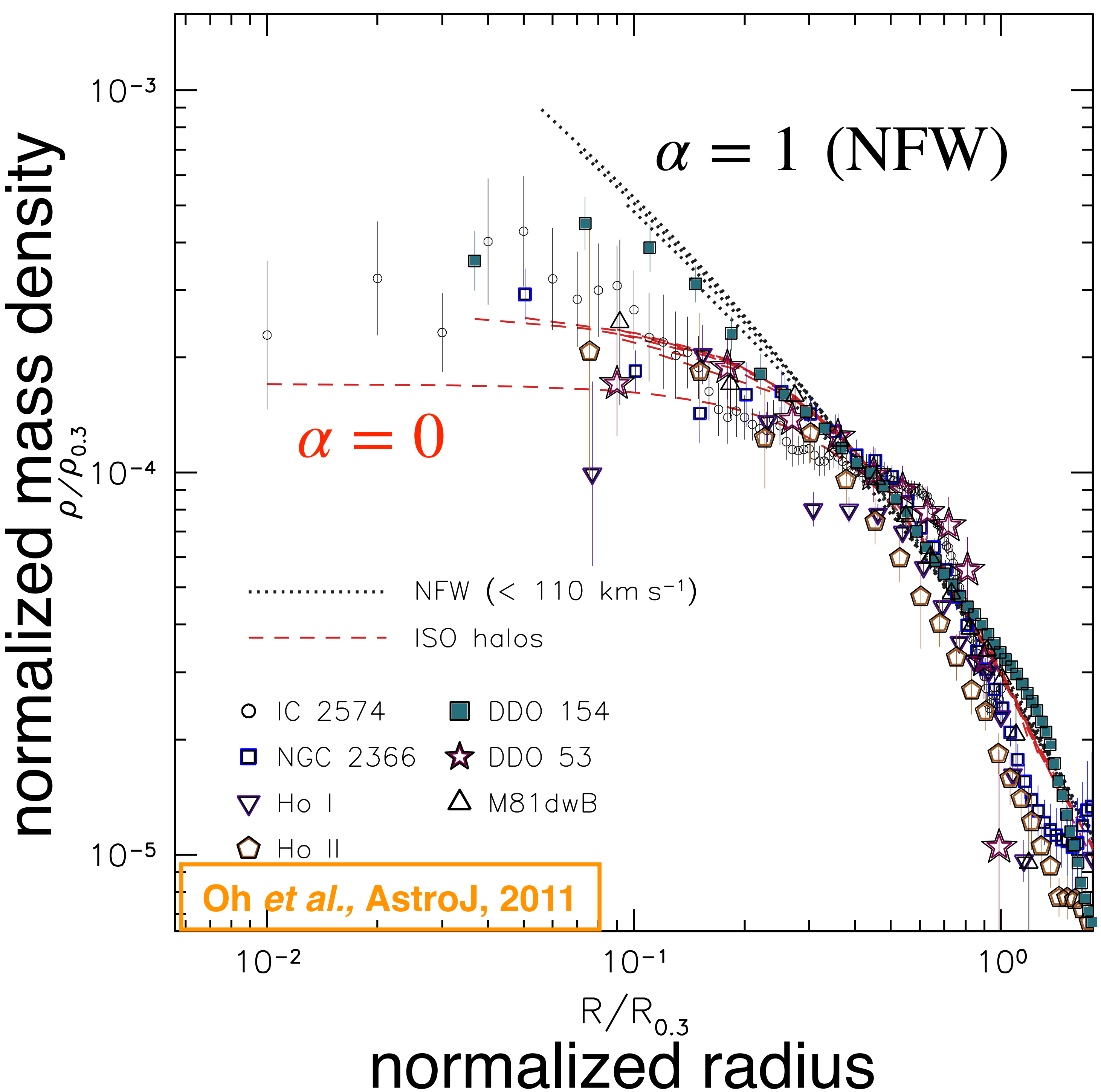
WDM reduces a predicted number of satellite galaxies

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



Cusp vs core problem

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



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

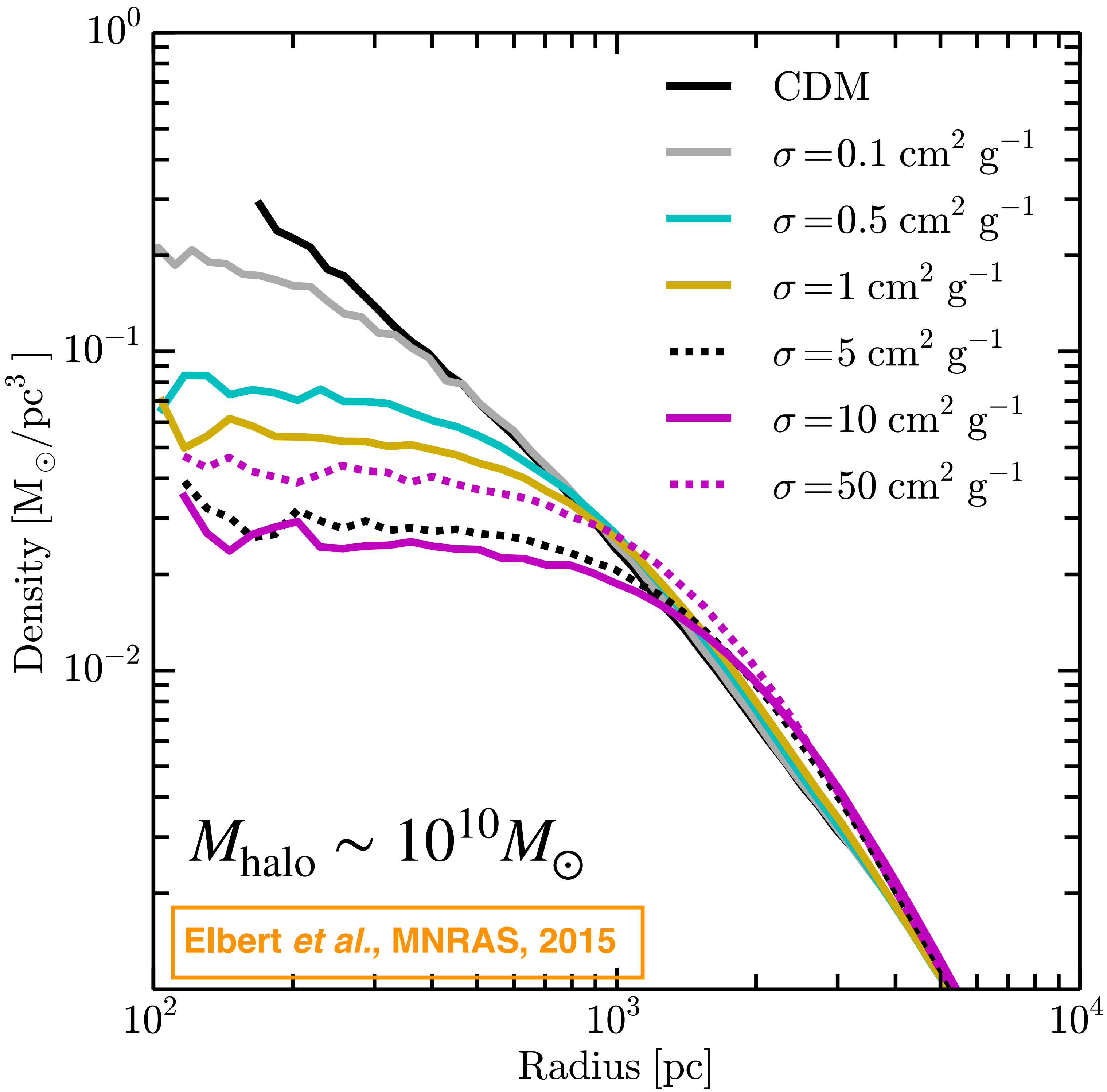
Observations infer cored profile in the inner region rather than cuspy NFW profile

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

- field dwarf spheroidal galaxies

$\sim 10^9\, M_\odot$

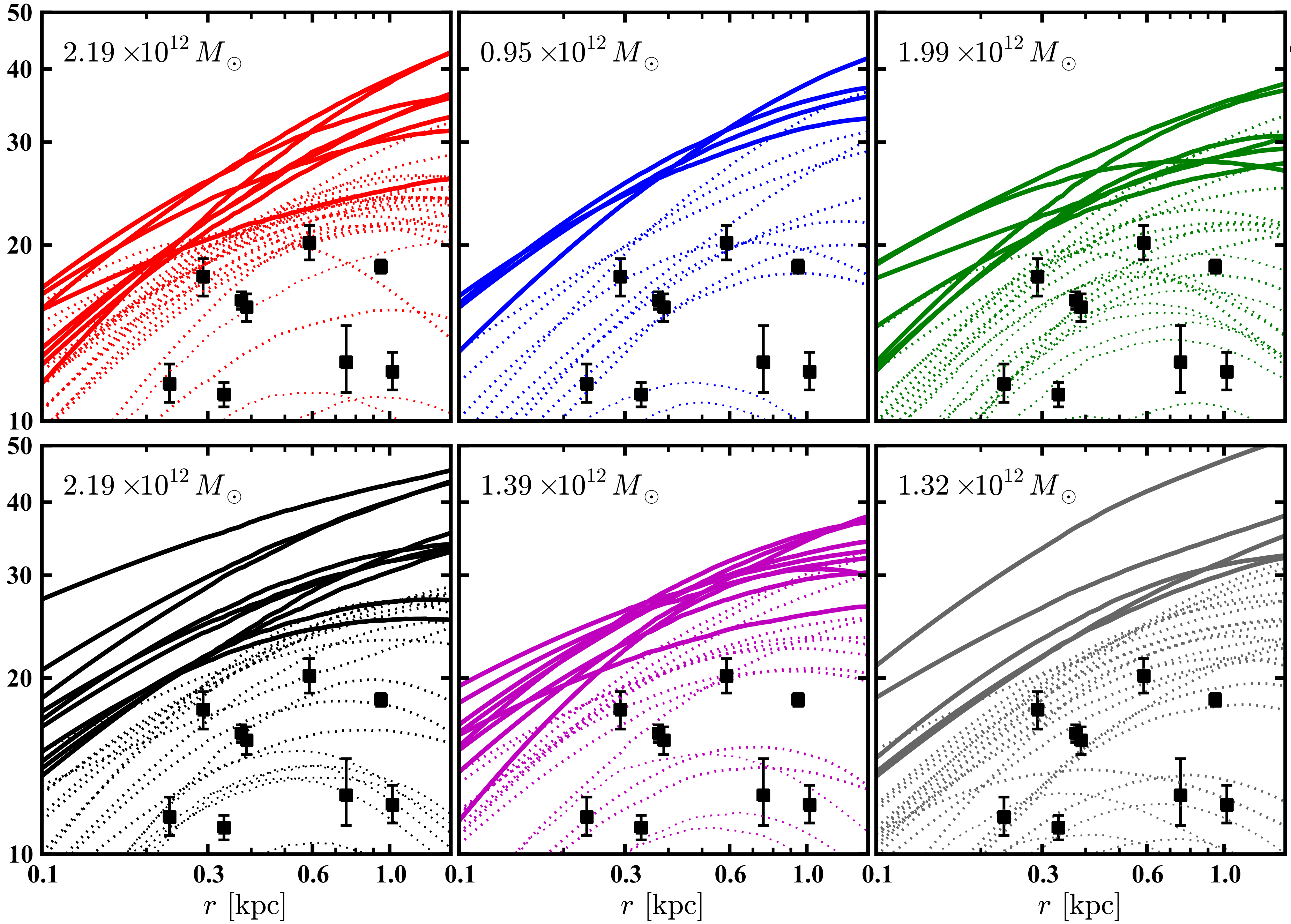
Cusp vs core problem w/ SIDM



SIDM reduces the central mass density

Too-big-to-fail problem

N-body (DM-only) simulations in the ΛCDM model →
~ 10 missing galaxies are the biggest subhalos in simulations
(to big to fail to be detected)



- MW-like halos

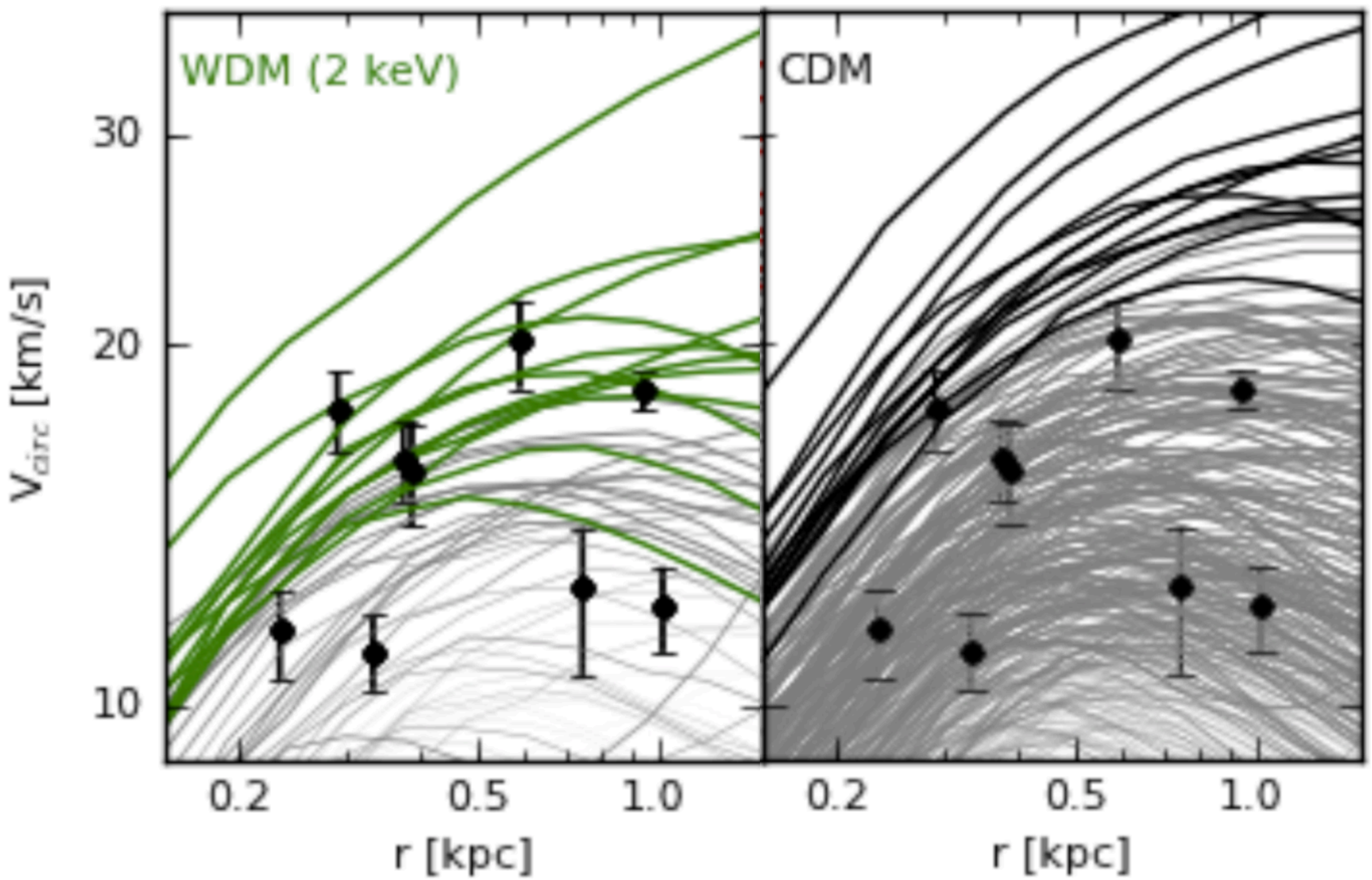
circular velocity of subhalos

radius

Boylan-Kolchin *et al.*, MNRAS, 2011

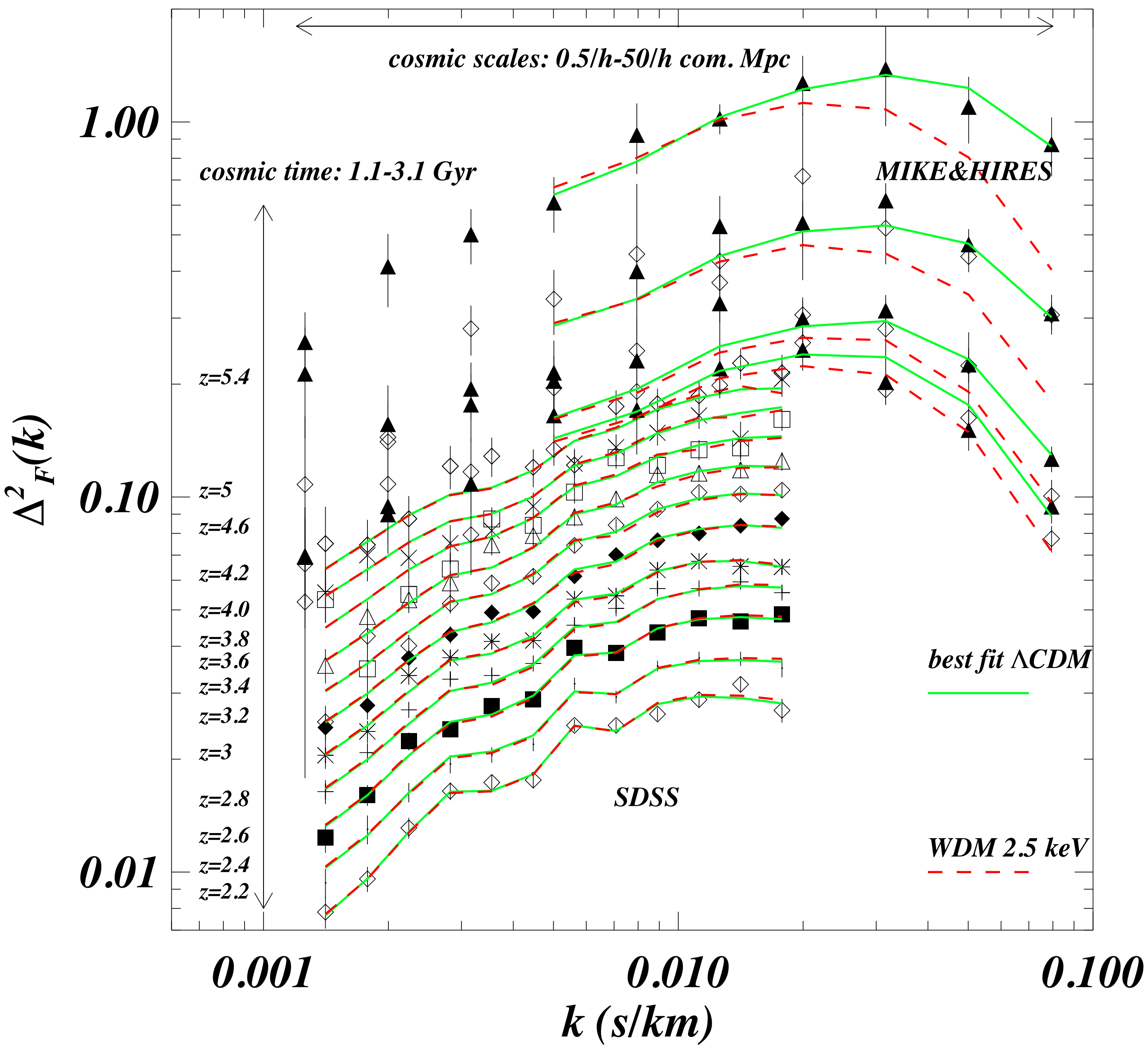
Too-big-to-fail problem w/ WDM

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



WDM reduces a predicted number of bigger subhalos than observed satellites

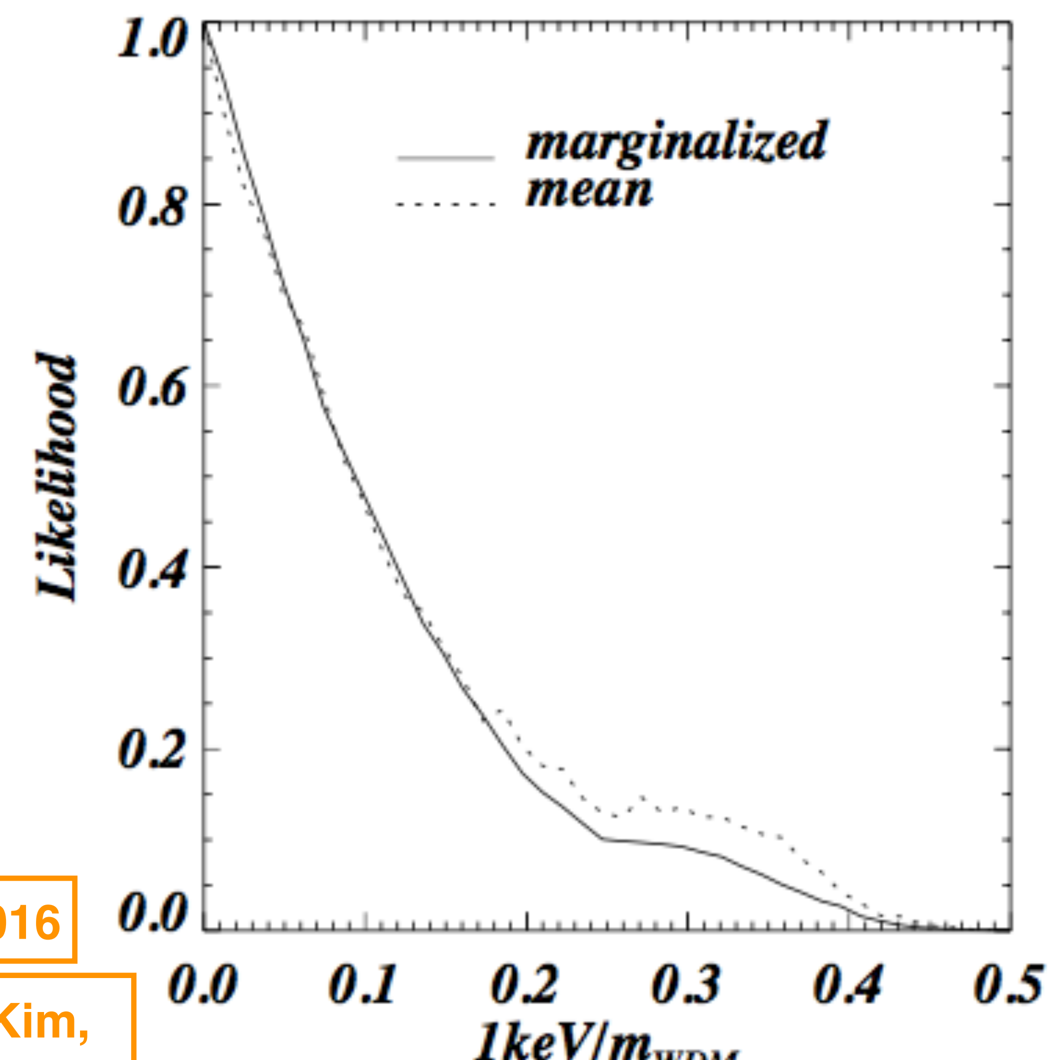
Lyman-α forest constraints on WDM



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

Summary

Dark matter cannot be explained in the standard model

infers physics beyond the standard model

WIMP is well-motivated in synergy with naturalness problem

under intensive investigation

No naturalness from LHC

WIMP miracle may have been gone…

- new theoretical reasoning for WIMP dark matter?
- beyond WIMP dark matter from small-scale issues?

Thank you for your attention

Discussion

More on…

Coincidence problem?

- asymmetric dark matter

Thermal freeze-out?

- semi-annihilation

Structure formation of WIMPs

- wino dark matter

Small-scale issues?

- diversity problem and self-interacting dark matter

Coincidence problem

Composite asymmetric dark matter

Why is a dark matter particle long-lived?

- new accidental $U(1)_{B'}$ (like $U(1)_B$ for proton)
- decay operator: non-renormalizable $\Lambda_{\mathrm{QCD}'}/M_* \ll 1$
- B' number asymmetry - cogenesis

Portal operator

$$\mathscr{L}_{\mathrm{portal}} = \frac{1}{M_*^n}\mathcal{O}_{\mathrm{SM}}\mathcal{O}_D$$: n+4 dim.

$*$ when no particle charged under both gauge groups

$\mathcal{O}_{\mathrm{SM}\,(D)}$: SM (D) gauge neutral, but $U(1)_{B-L}$ ($U(1)_{B'}$) charged

→ at high energy (temperature) , $Y_{\Delta(B-L)} \leftrightarrow Y_{\Delta B'}$

$Y_{\Delta B'} \sim Y_{\Delta B}$ $m_{N'} \sim \Lambda_{\mathrm{QCD}'} = \mathcal{O}(1)\,\mathrm{GeV}$ → $\Omega_{\mathrm{dm}}h^2 \simeq 5\Omega_{\mathrm{baryon}}h^2 \simeq 0.12$

- close to SM QCD dynamical scale

Thermal history

SM | dark

$Y_{\Delta(B-L)} \sim Y_{\Delta B'}$

portal operator decoupled $T \sim M_*(M_*/M_{\rm pl})^{1/(2n-1)}$

$U(1)_{B-L}$ $Y_{\Delta(B-L)}$

$U(1)_{B'}$ $Y_{\Delta B'}$

sphaleron process decoupled

$T \sim 100\,\mathrm{GeV}$

$U(1)_B \times U(1)_L$ $Y_{\Delta B}$ $Y_{\Delta L}$

QCD' phase transition

$T \sim \Lambda_{\rm QCD'}$

pair annihilation of nucleon's

$\rightarrow \Omega_{\rm DM'} h^2 \propto \Lambda_{\rm QCD'} Y_{\Delta B'}$

QCD phase transition

$T \sim \Lambda_{\rm QCD}$

pair annihilation of nucleons
into pions

$\rightarrow \Omega_{\rm baryon} h^2 \propto \Lambda_{\rm QCD} Y_{\Delta B}$

Simple model

Ibe, AK, Kobayashi, and Nakano, JHEP 2018

Model setup: QCD×QED-like hidden sector u' $\bar{u}'$ d' $\bar{d}'$

- dark nucleons as DM $p' \sim u'u'd'$ $n' \sim u'd'd'$

Right-handed neutrinos $\overline{N}$ w/ soft breaking mass M_R
and scalar down quark H'_C w/ mass $M_{H'_C}$ $U(1)_{B-L+B'} \to (-1)^{3(B-L+B')}$

- thermal leptogenesis → $B-L$ asymmetry

Fukugita and Yanagida, PLB, 1986

- see-saw mechanism → active neutrino mass

- only $\frac{y_N}{M_{H_C}^2 M_R}\bar{u}'\bar{d}'\bar{d}'LH$ and ✗ $\frac{y_N}{M_{H_C}^2 M_R}\bar{u}\bar{d}\bar{d}LH$ ➡ $m_{\rm DM} \simeq 8.5\,{\rm GeV}$

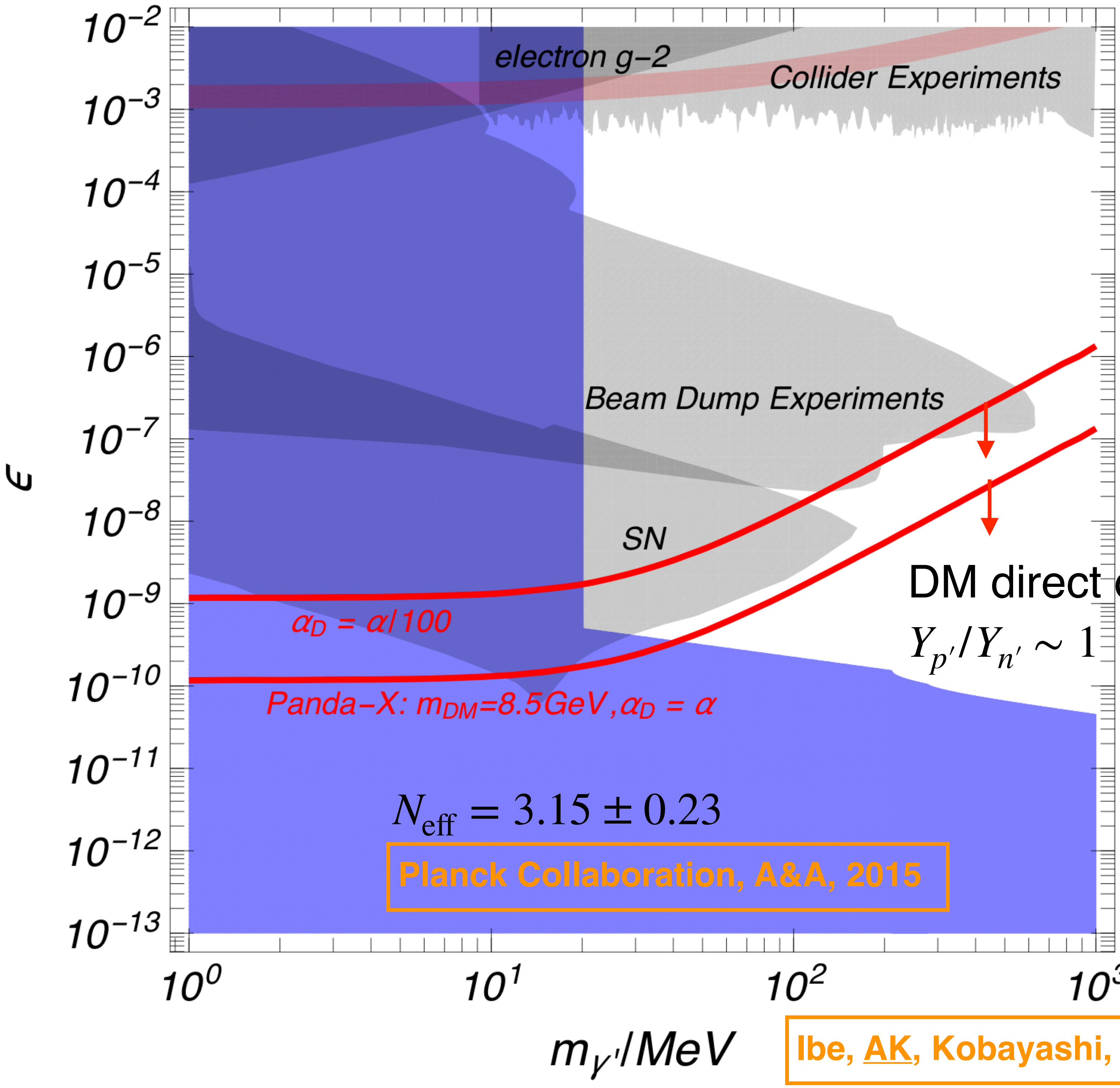
Kinetic mixing between SM and dark photons $\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$
and $U(1)'$ breaking scalar $H^{+'}$

- dark photon decay releases dark sector entropy

- direct detection: SM and dark protons scattering $Y_{p'}/Y_{n'}$?

Dark photon parameter plot

$$\Gamma_{\gamma' \to e\bar{e}} = 0.3\,\mathrm{s}^{-1} \times \left(\frac{\epsilon}{10^{-10}}\right)^2 \left(\frac{m_{\gamma'}}{100\,\mathrm{MeV}}\right)$$



Del Nobile, Kaplinghat, and Yu, JCAP, 2015

- chance to see QCD-like asymmetric dark matter in near-future

Ibe, AK, Kobayashi, and Nakano, JHEP 2018

Origin of kinetic mixing

Ibe, AK, Kobayashi, Kuwahara and Nakano, JHEP, 2019

Grand unifications in both SM and dark sectors $SU(5) \times SU(4)'$

* mass splitting

$m_{d'} < \Lambda_{\mathrm{QCD}'} < m_{e'}$

: dark nucleon decay

$M_{H_C'} \gg m_{H^{+'}}$: portal operator

$\mathbf{6}' : (u', \bar{u}')$ $\mathbf{4}' : (d', \bar{e}')$ $\bar{\mathbf{4}}' : (\bar{d}', e')$

$\mathbf{4}_H' : (H_C', H^{+'})$ - $U(1)'$ breaking

- portal operator

- particles we introduce so far except for e' form $SU(4)'$ multiplets

Higher dimensional operator

$$\mathscr{L}_{\mathrm{mix}} \sim \frac{1}{M_{\mathrm{pl}}^2} \mathrm{Tr}\left(F_{\mathrm{GUT}\mu\nu} \Sigma_{\mathrm{GUT}}\right) \mathrm{Tr}\left(F_{\mathrm{GUT}'}^{\mu\nu} \Sigma_{\mathrm{GUT}'}\right)$$

Σ: adjoint scalar

$$\to 10^{-10} \left(\frac{v_{24}}{10^{16}\,\mathrm{GeV}}\right)\left(\frac{v_{15}}{10^{10}\,\mathrm{GeV}}\right) F_{\mu\nu} F'^{\mu\nu}$$

$$\sim M_{H_C} > M_R > 10^9\,\mathrm{GeV}$$

Supersymmetric realization

Precise $SU(5)$ grand unification and origins of electroweak and $U(1)'$ breaking → SUSY

Ibe, AK, Kobayashi, Kuwahara and Nakano, JHEP, 2019

Dark sector $SU(4)'$ $\mathbf{6}' : (u', \overline{u}')$ $\mathbf{4}' : (d', \overline{e}')$ $\overline{\mathbf{4}}' : (\overline{d}', e')$

$$\mathbf{4}'_H : (H'_C, H^{+'}) \quad \overline{\mathbf{4}}'_H : (\overline{H}'_C, H^{-'})$$

Portal superpotential

$$W \sim \frac{y_N}{M_{H_C} M_R} \overline{u}' \overline{d}' \overline{d}' L H_u$$

$$\xrightarrow{\tilde{\overline{d}}'} \mathscr{L} \sim \frac{\alpha'}{4\pi} \frac{y_N}{M_{H_C} M'_S M_R} \overline{u}' \overline{d}' \overline{d}' L H_u$$

dark nucleon decay into neutrino → $\lesssim \dfrac{1}{10^{26}\,\mathrm{GeV}^3}$

$n' \to \pi^{0'} + \nu \qquad \tau \gtrsim 10^{23}\,\mathrm{sec}$

Covi, Grefe, Ibarra, and Tran, JCAP, 2010

Fukuda, Matsumoto, and Mukhopadhyay, PRD, 2015

hidden sparticle mass $M'_S \gtrsim 10^3\,\mathrm{GeV} \left(\dfrac{M_R}{10^9\,\mathrm{GeV}} \right)^{1/2}$ - split SUSY!

Mirror grand unification

Ibe, AK, Kobayashi, Kuwahara and Nakano, arXiv:1907.03404

Dream $SU(5) \times SU(4)' \to SU(5) \times SU(5)'/\mathbb{Z}_2$

$\mathbf{10} : (Q, \overline{u}, \overline{e})$ $\quad \overline{\mathbf{5}} : (\overline{d}, \widehat{L})$

$\mathbf{5}_H : (H_C, H_u)$ $\quad \overline{\mathbf{5}}_H : (\overline{H}_C, \widehat{H}_d)$

$\mathbf{10}' : (\mathbf{6}'(u', \overline{u}') + \mathbf{4}'(d', \overline{e}'))$

$\overline{\mathbf{5}}' : (\overline{\mathbf{4}}'(\overline{d}', e'), -\nu')$

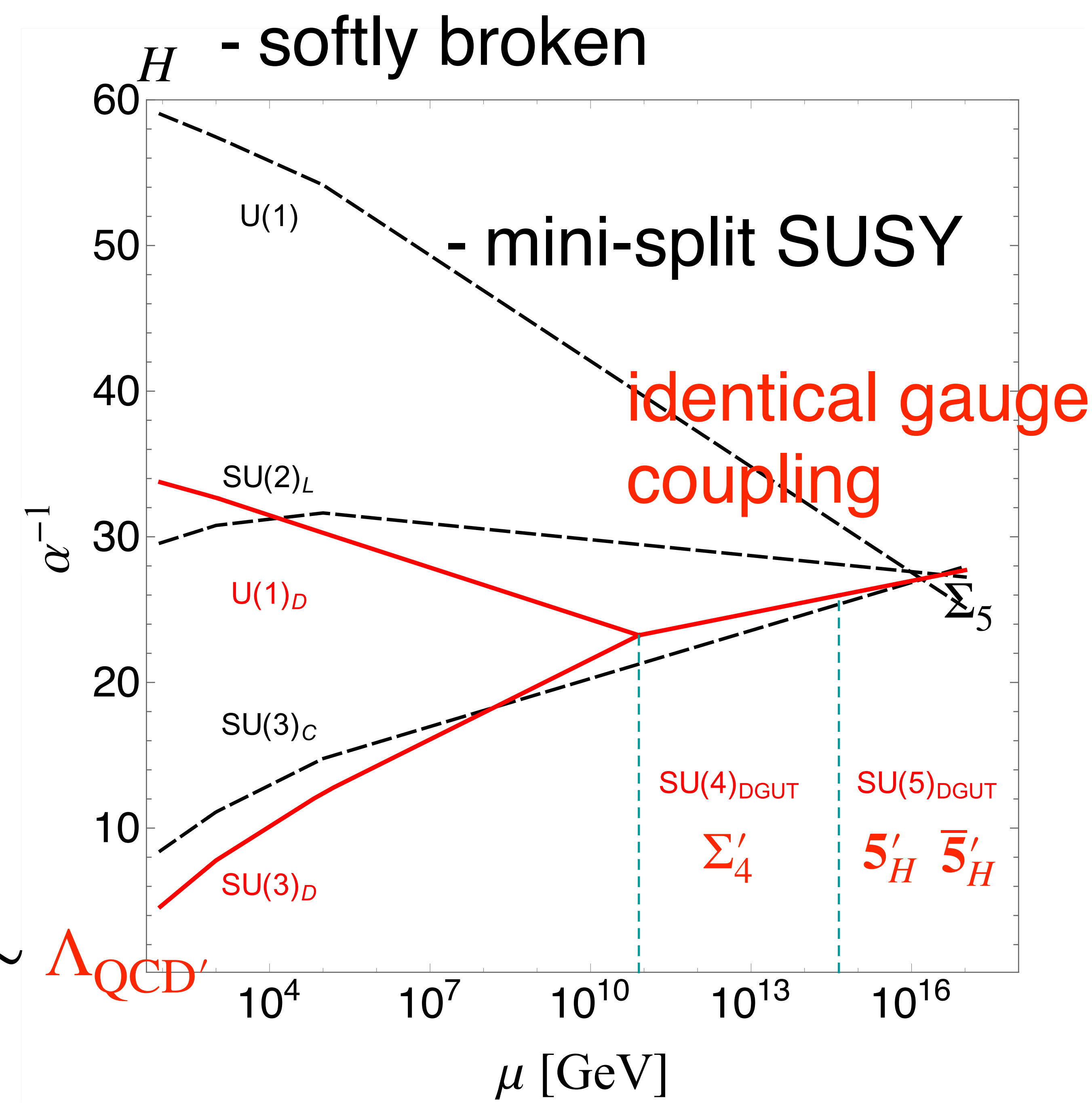
$\mathbf{5}'_H : (\mathbf{4}'_H(H'_C, H^{+'}_u), H^{0'}_u)$

$\overline{\mathbf{5}}'_H : (\overline{\mathbf{4}}'_H(\overline{H}'_C, H^{-'}_d), -H^{0'}_d)$

large VEV

→ vector-like theory

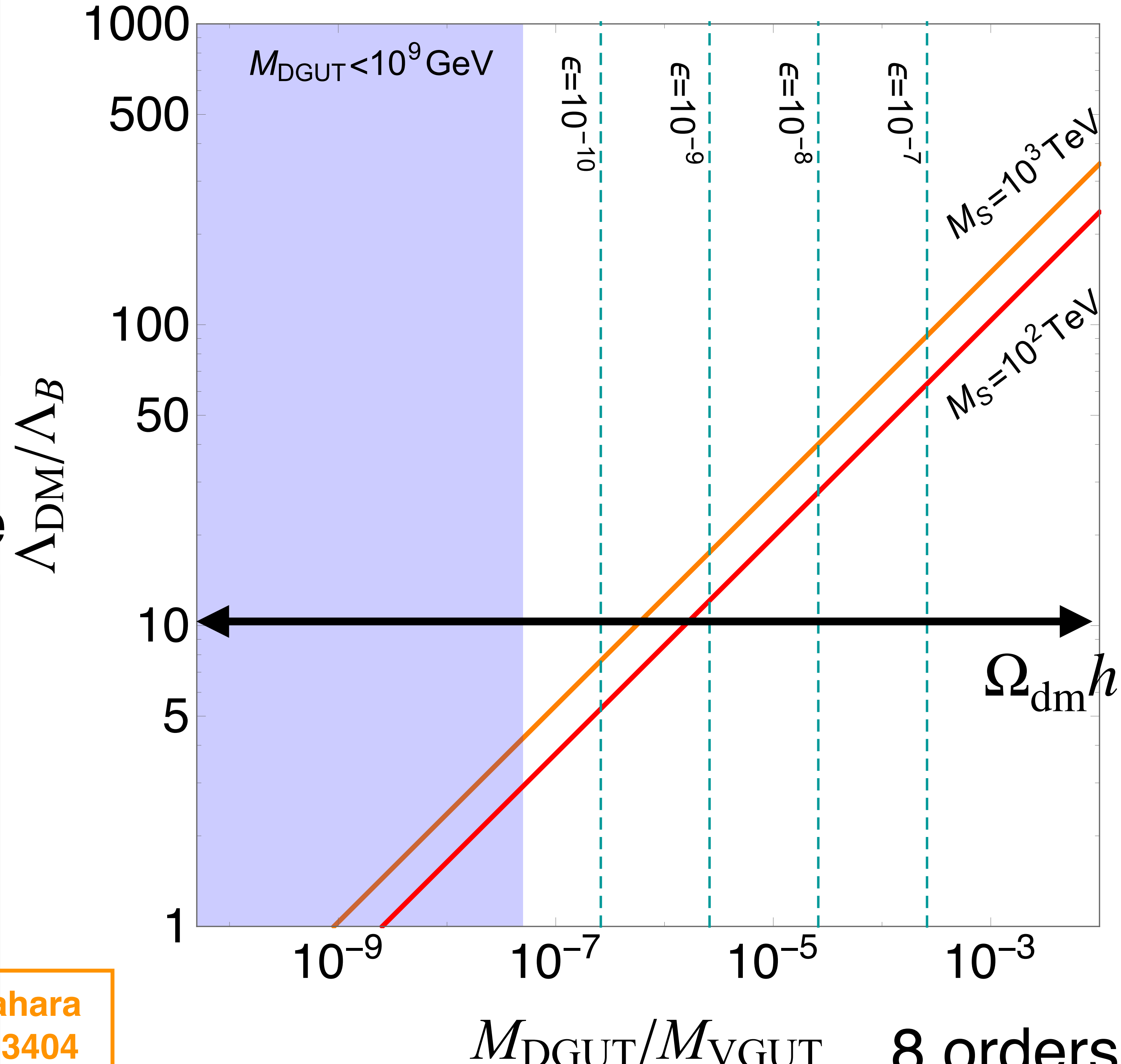
$\Lambda_{\rm QCD} \sim \Lambda_{\rm QCD'}$



Alleviating coincidence

Why $\Omega_{\rm dm}h^2 \sim \Omega_{\rm baryon}h^2$ or $\Lambda_{\rm QCD} \sim \Lambda_{\rm QCD'}$?

just 3 orders of magnitude



$\Omega_{\rm dm}h^2 \simeq 5\Omega_{\rm baryon}h^2$

8 orders of magnitude

Ibe, <u>AK</u>, Kobayashi, Kuwahara and Nakano, arXiv:1907.03404

Thermal freeze-out

WIMP freeze-out

Boltzmann equation for WIMP freeze-out

Kolb and Turner, The Early Universe

$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = -\langle\sigma_{\rm ann}v\rangle(n_{\rm DM}^2 - n_{\rm DM}^{\rm eq\,2})$$

- adiabatic evolution - annihilation - part-creation

$n_{\rm DM} \propto 1/a^3$ $\langle\sigma_{\rm ann}v\rangle$: thermally averaged cross section

$$n_{\rm DM}^{\rm eq} = g_{\rm DM}\left(\frac{m_{\rm DM}T}{2\pi}\right)^{3/2}\exp(-m_{\rm DM}/T)$$

: equilibrium number density w/ # of spin d.o.f being $g_{\rm DM}$

Derived under two assumptions:

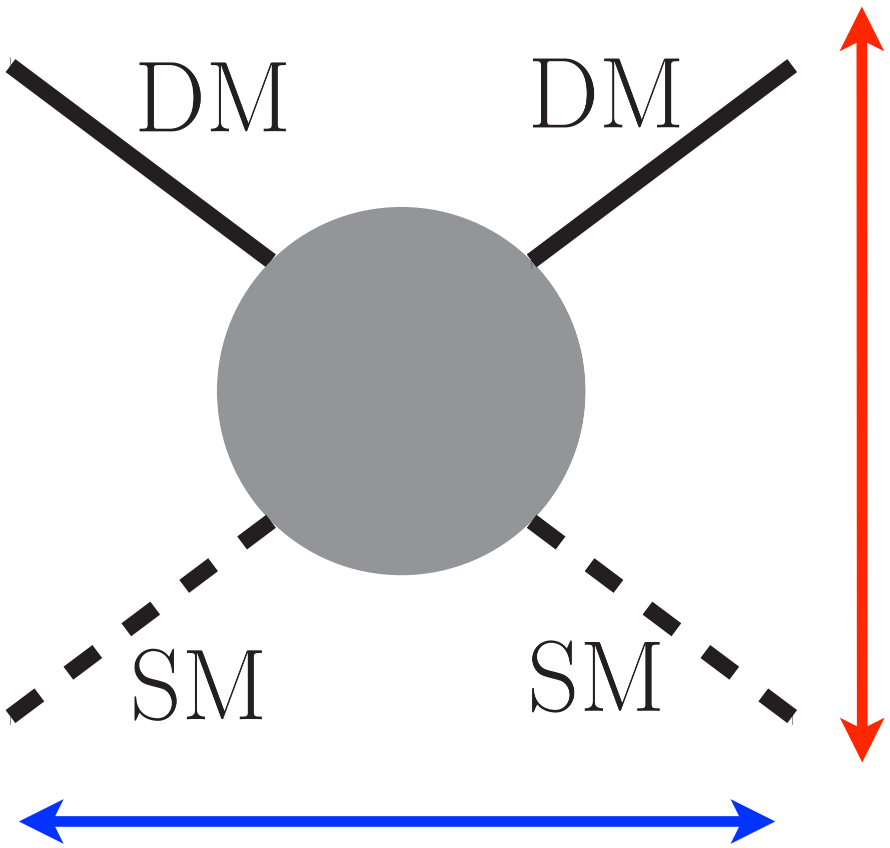
$\mathscr{T}$ invariance ↔ $|\mathscr{M}_{\rm for}|^2 = |\mathscr{M}_{\rm back}|^2$ w/ spin and momentum flipped

→ *detailed balance*: (r.h.s) = 0 for $n_{\rm DM} = n_{\rm DM}^{\rm eq}$

kinetic equilibrium ↔ $f_{\rm DM} = \dfrac{n_{\rm DM}}{n_{\rm DM}^{\rm eq}(T)}\exp(-E/T)$ T : SM temperature

- how to validate?

(In)elastic proceses



inelastic (chemical) process

- change number
- exchange energy w/ SM particles

crossing symmetry for WIMP →
elastic process ↔ inelastic process

elastic (kinetic) process

- unchange number
- exchange energy w/ SM particles

Efficient elastic process → kinetic equilibrium

Kinetic equilibration rate

Fokker-Planck approximation:
expanding the collision term w.r.t. $q \ll p$

Binder, Covi, AK, Murayama, Takahashi, and Yoshida, JCAP, 2016

T : temperature
u^μ : bulk velocity
of thermal plasma - TP

$$C[f_{\mathrm{DM}}] = m_{\mathrm{DM}} \frac{\partial}{\partial \mathbf{p}_{\mathrm{DM}}} \left[\gamma \left(m_{\mathrm{DM}} T \frac{\partial f_{\mathrm{DM}}}{\partial \mathbf{p}_{\mathrm{DM}}} + (\mathbf{p}_{\mathrm{DM}} - m_{\mathrm{DM}} \mathbf{u}) f_{\mathrm{DM}} \right) \right]$$

$$\gamma = \frac{1}{6 m_{\mathrm{DM}} T} \sum_{s_{\mathrm{TP}}} \int \frac{d^3 \mathbf{p}_{\mathrm{TP}}}{(2\pi)^3} f_{\mathrm{TP}}^{\mathrm{eq}} (1 \mp f_{\mathrm{TP}}^{\mathrm{eq}}) \int_{-4\mathbf{p}_{\mathrm{TP}}^2}^{0} dt (-t) \frac{d\sigma}{dt} v$$

$\propto p^2$ - thermal momentum squared

$\propto q^2$ - momentum transfer squared

➡ Kinetic equilibrium is usually a valid assumption $\gamma / H \gg 1$
exception: resonant annihilation

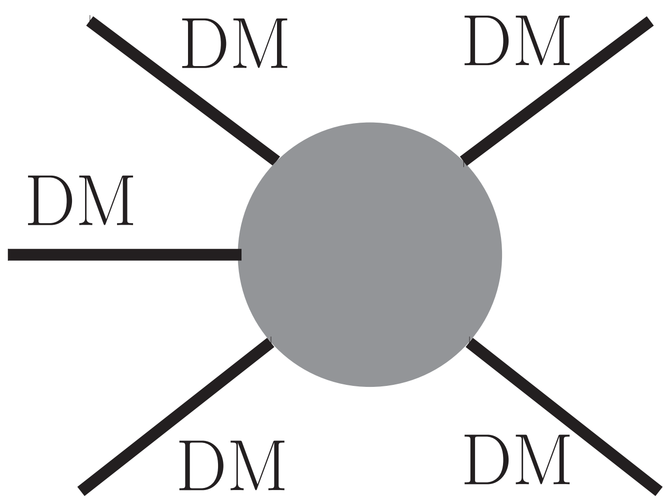
Binder, Bringmann, Gustafsson, Hryczuk, PRD, 2017

Kinetic equilibration for beyond WIMP

Inelastic process has nothing to do with elastic process

➡ co-evolution of $n_{\rm DM}$ & $T_{\rm DM}$

3→2 process:



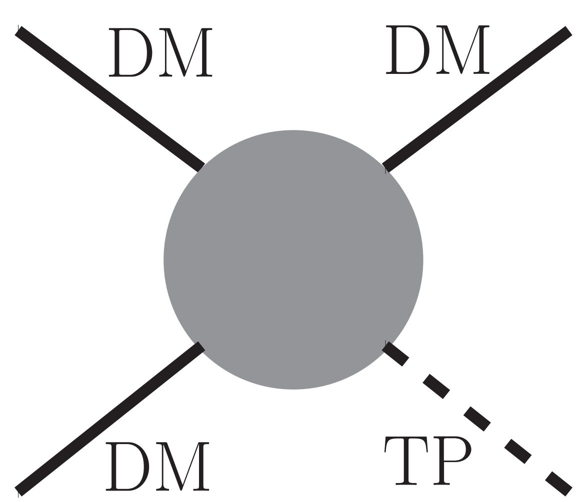
Entropy conservation

➡ $Y = n_{\rm DM}/s \propto 1/\ln a$

$T_{\rm DM} \propto 1/\ln a$

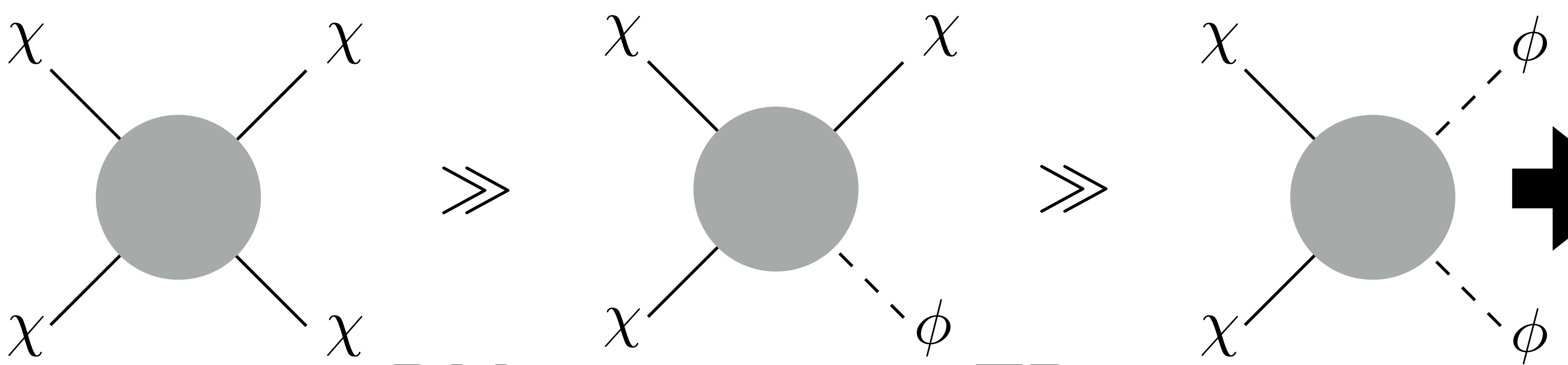
Carlson, Machacek, and Hall, APJ, 1992

Semi-annihilation:



➡ Solve co-evolution equations

Co-evolution equations



- DM   - TP

efficient self-scattering

$$\Rightarrow \quad f_\chi = \frac{n_\chi}{n_\chi^{\rm eq}(T_\chi)} \exp(-E_\chi/T_\chi)$$

Co-evolution equations: AK, Kim, Kim, and Sekiguchi, PRL, 2018

$T_\chi = T_\phi$

$\Downarrow$ Boltzmann equation for WIMP freeze-out

$$\dot{n}_\chi + 3Hn_\chi = -\, n_\chi \langle \sigma_{\rm semi} v \rangle_{T_\chi T_\chi} \left[n_\chi - \mathcal{J}(T_\chi, T_\phi) n_\chi^{\rm eq}(T_\chi) \right]$$

$$\dot{T}_\chi + 3HT_\chi \left(\frac{T_\chi}{\sigma_E} \right)^2 = -\left(\frac{T_\chi}{\sigma_E} \right)^2 \frac{n_\phi^{\rm eq}(T_\chi)}{n_\chi^{\rm eq}(T_\chi)} \langle \Delta E \sigma_{\rm inv} v \rangle_{T_\chi, T_\phi = T_\chi} \times \left[n_\chi - n_\chi^{\rm eq}(T_\chi) \mathcal{K}(T_\chi, T_\phi) \right]$$

- adiabatic cooling

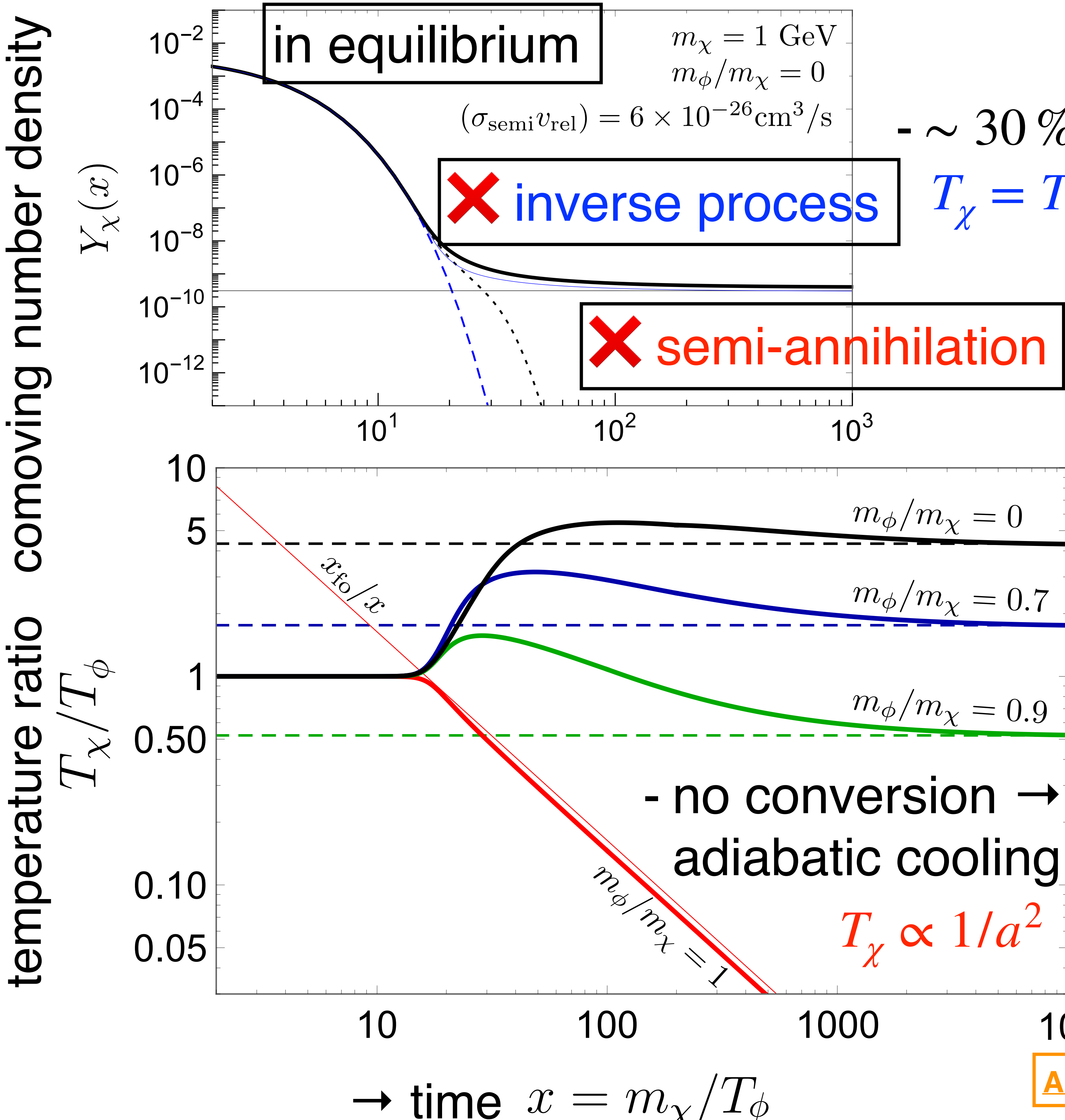
- heating through semi-annihilation

relativistic: $\sigma_E^2 = 3T_\chi \;\rightarrow\; T_\chi \propto 1/a$

non-relativistic: $\sigma_E^2 = 3/2T_\chi \rightarrow T_\chi \propto 1/a^2$

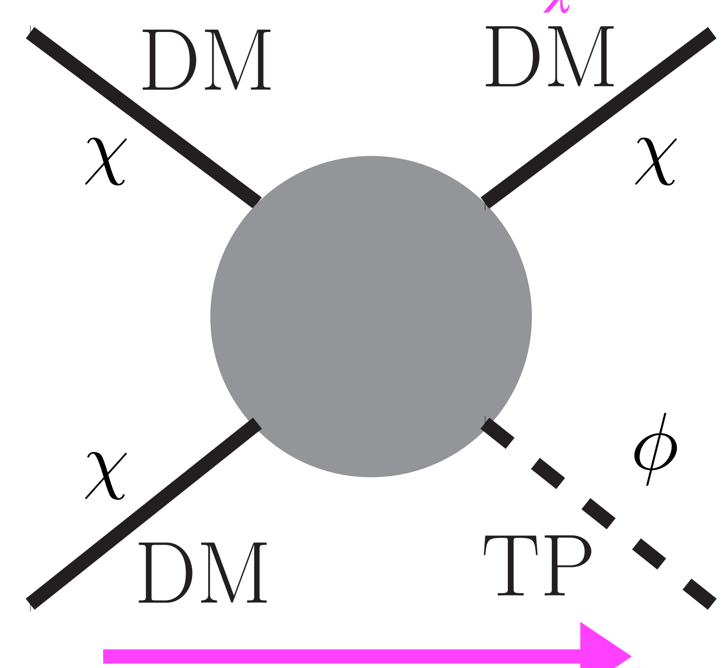
$$\sigma_E^2 = \langle E_\chi^2 \rangle - \langle E_\chi \rangle^2$$

Freeze-out



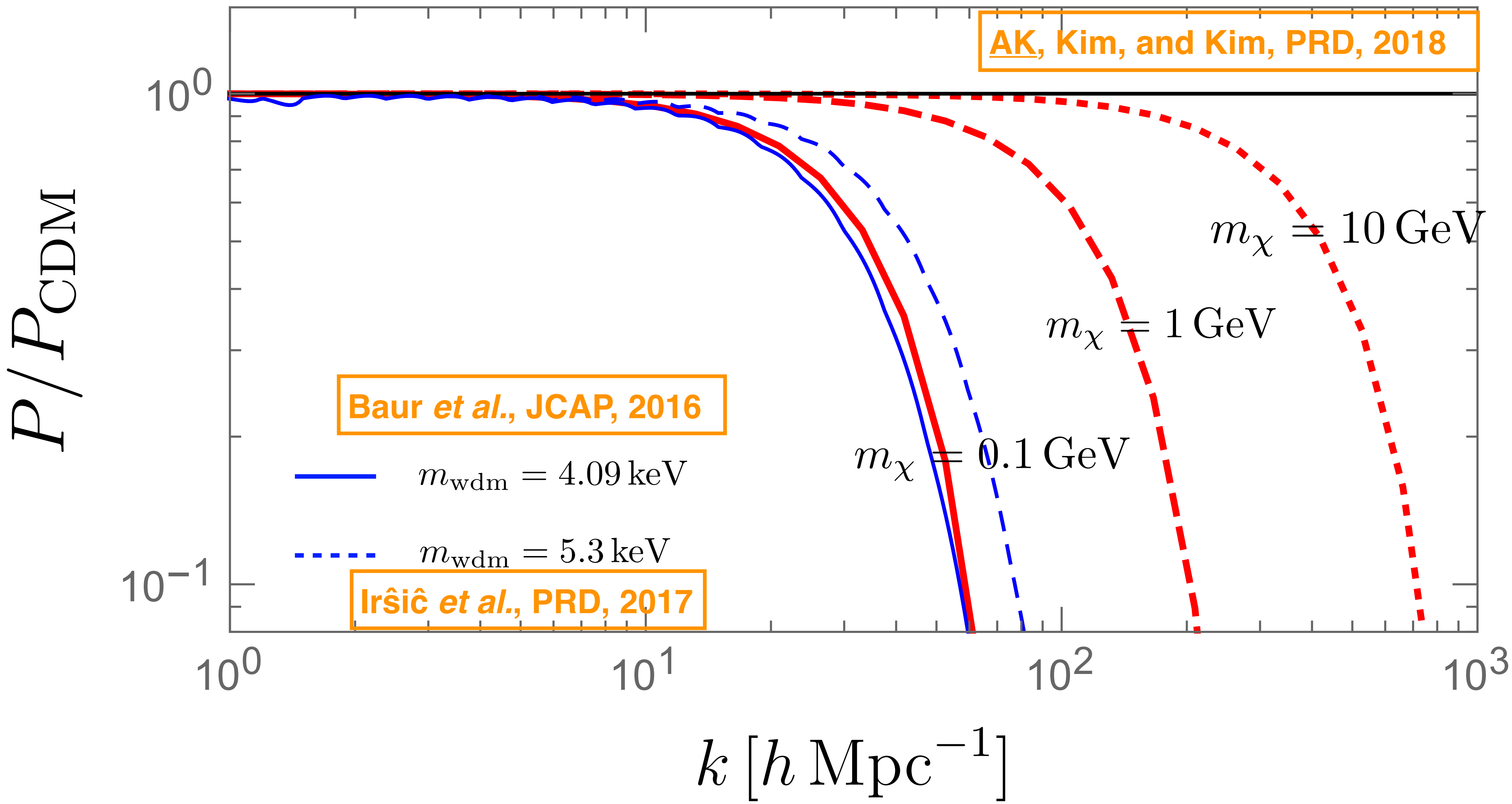
- $\sim 30\,\%$ difference from $T_\chi = T_\phi \propto 1/a$

- mass deficit converted into the kinetic energy → self-heating $T_\chi \propto 1/a$



AK, Kim, Kim, and Sekiguchi, PRL, 2018

Galactic-scale structure formation



Self-heating ceases when self-scattering becomes inefficient $T_{\rm self}$

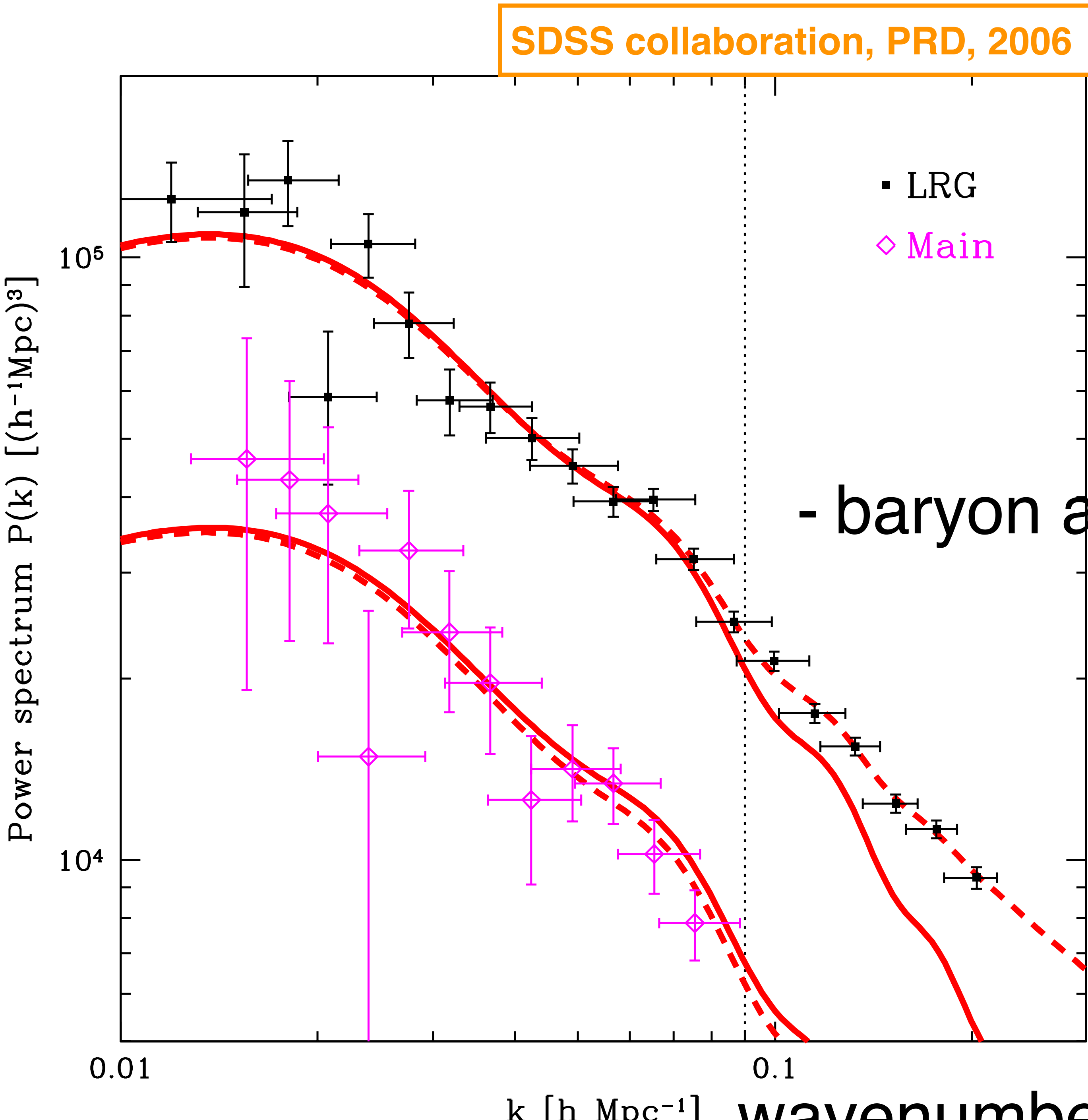
Warmness (WDM) is related with self-scattering (SIDM)

$$\frac{m_{\rm wdm}}{5.3\,{\rm keV}} \simeq 3\left(\frac{m_\chi}{1\,{\rm GeV}}\right)^{3/8} \max\left(1, \sqrt{\frac{T_{\rm self}}{T_{\rm eq}}}\right)^{3/4} \left(\frac{T_\chi}{T}\right)^{-3/8}_{\rm asy}$$

Structure formation of WIMPs

Baryon acoustic oscillation

Baryons are involved in plasma acoustic oscillation until decoupling (recombination)



matter power spectrum

wavenumber

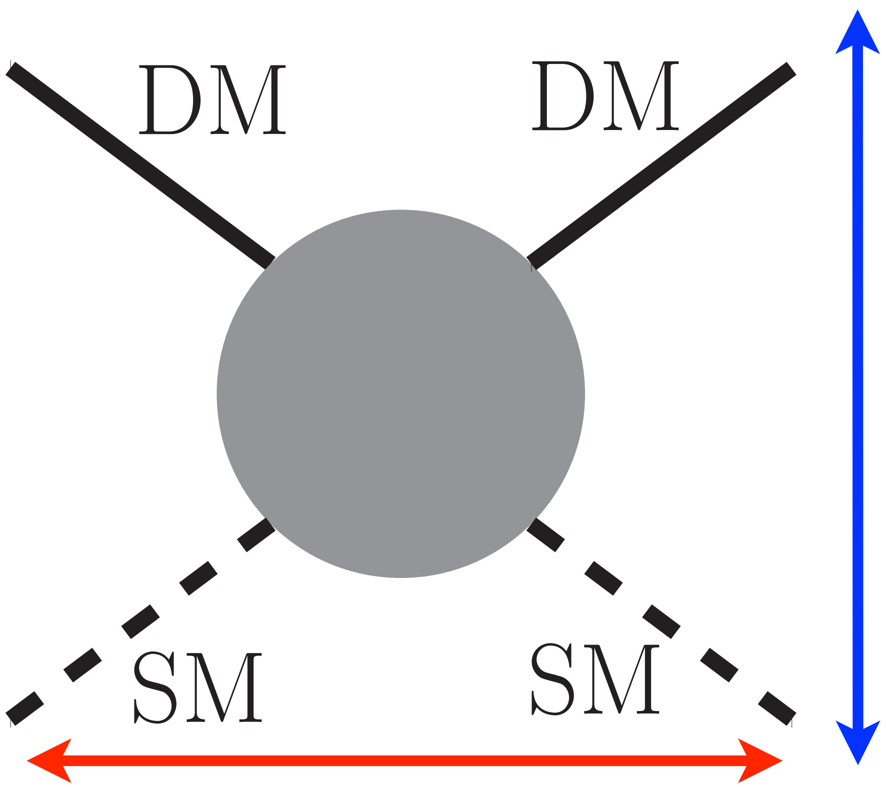
- baryon acoustic oscillation

wiggles on the horizon scale at decoupling are imprinted on the matter power spectrum

observed in galaxy clustering

Dark acoustic oscillation

WIMPs (weakly interacting massive particles) are in thermal equilibrium in the early Universe



Crossing symmetry:
elastic scattering usually lasts even after freeze-out (decoupling of annihilation)

Gondolo, Edsjo, Ullio, Bergstrom, Schelke, and Baltz, JCAP, 2004

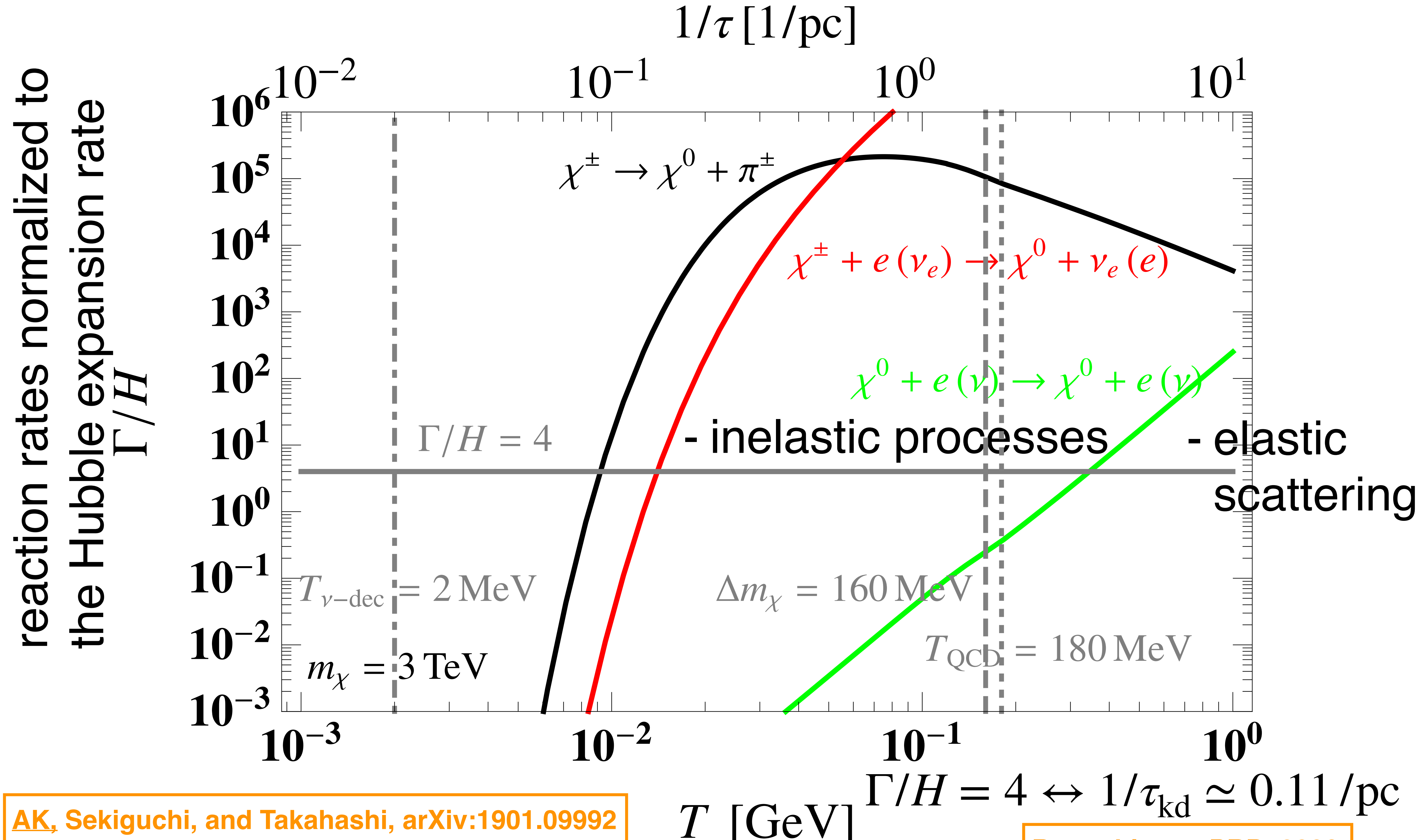
Profumo, Sigurdson, and Kamionkowski, PRL, 2006

Dark matter is involved in plasma acoustic oscillation until kinetic decoupling - dark acoustic oscillation

horizon scale at decoupling ↔ smallest (proto) halos

→ may impact indirect detection signals

Kinetic decoupling of wino DM



$\Gamma/H = 4 \leftrightarrow 1/\tau_{\mathrm{kd}} \simeq 0.11\,/\mathrm{pc}$

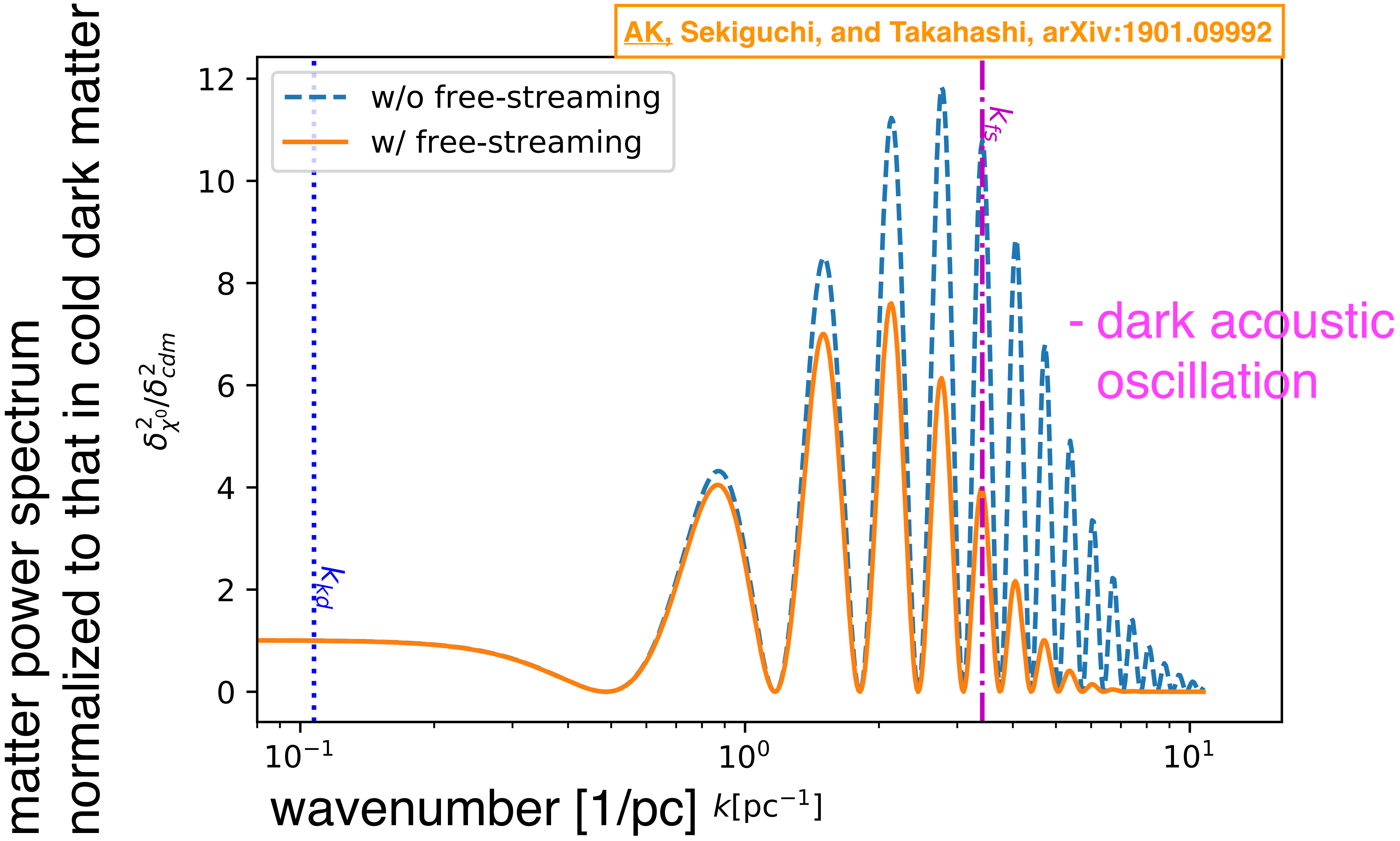
AK, Sekiguchi, and Takahashi, arXiv:1901.09992

Bertschinger, PRD, 2006

Inelastic processes with charginos involve neutralinos in dark acoustic oscillation

Power spectrum

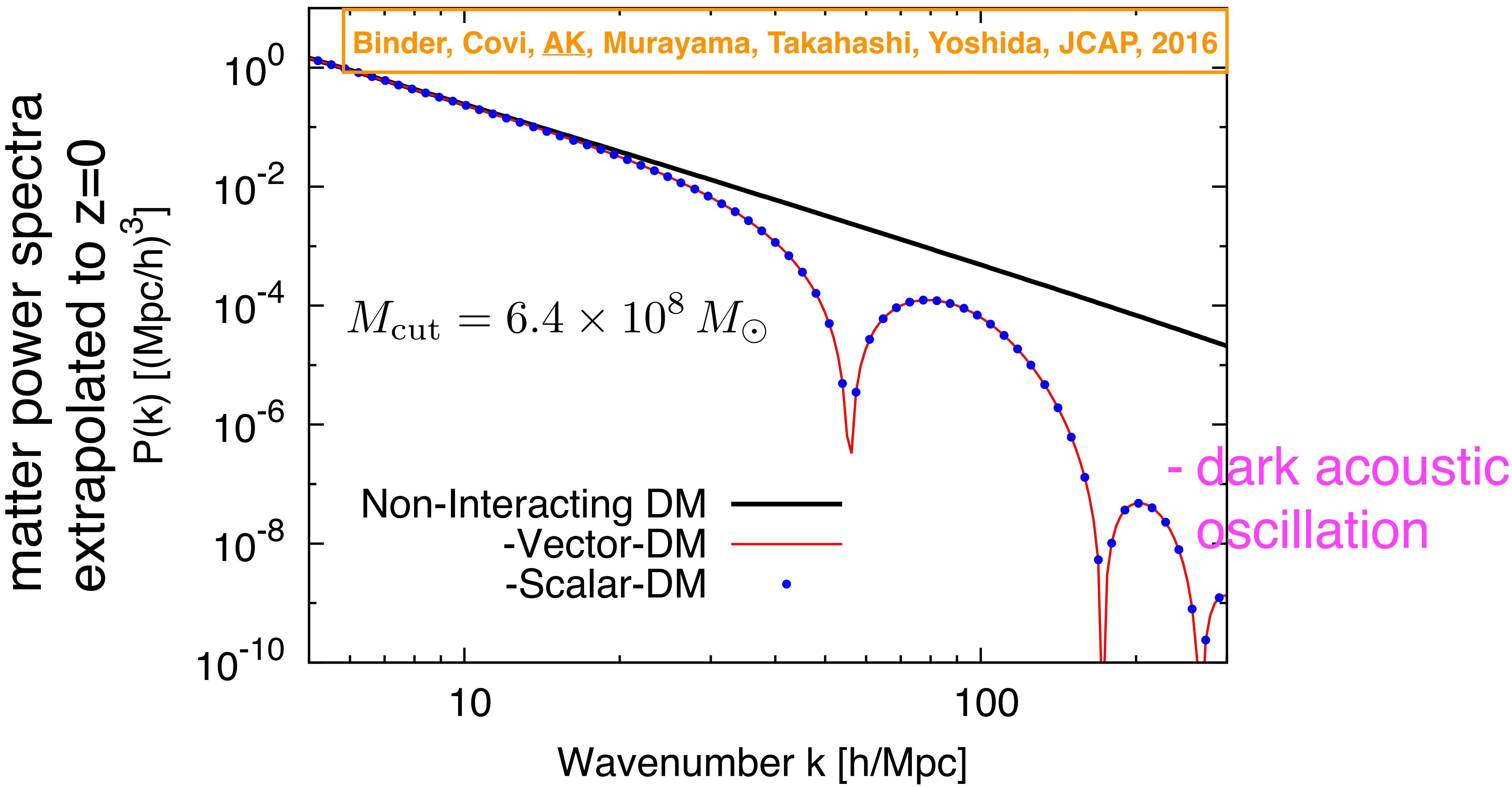
Wino dark matter - inelastic scattering



Peak amplitudes are enhanced!: overshooting phenomenon

Power spectrum

Typical WIMPs - elastic scattering

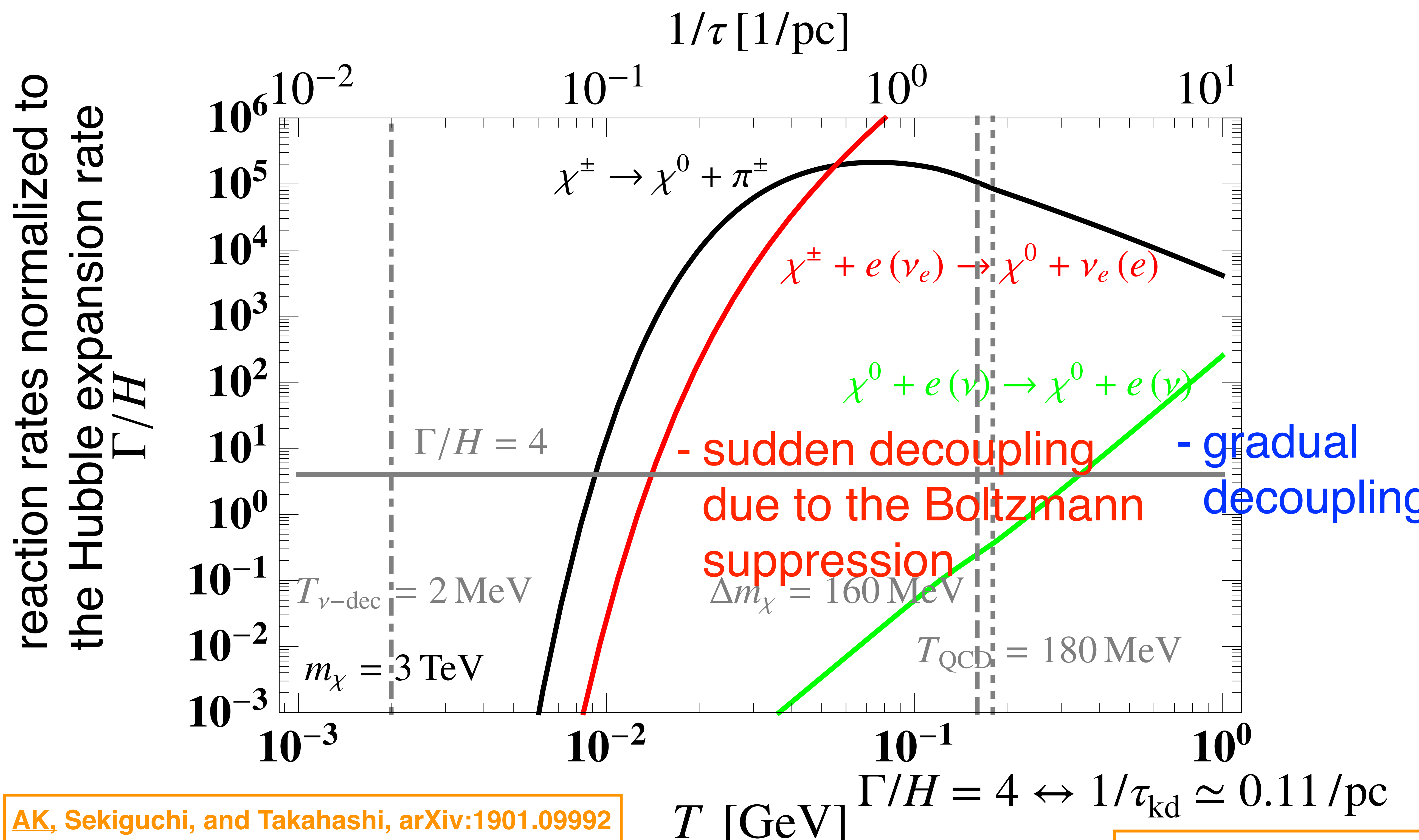


Peak amplitudes are damped

- Landau damping known for baryon acoustic oscilllation

Oscillation phase is averaged over the finite duration of decoupling

Kinetic decoupling



AK, Sekiguchi, and Takahashi, arXiv:1901.09992

$\Gamma/H = 4 \leftrightarrow 1/\tau_{\rm kd} \simeq 0.11\,/\mathrm{pc}$

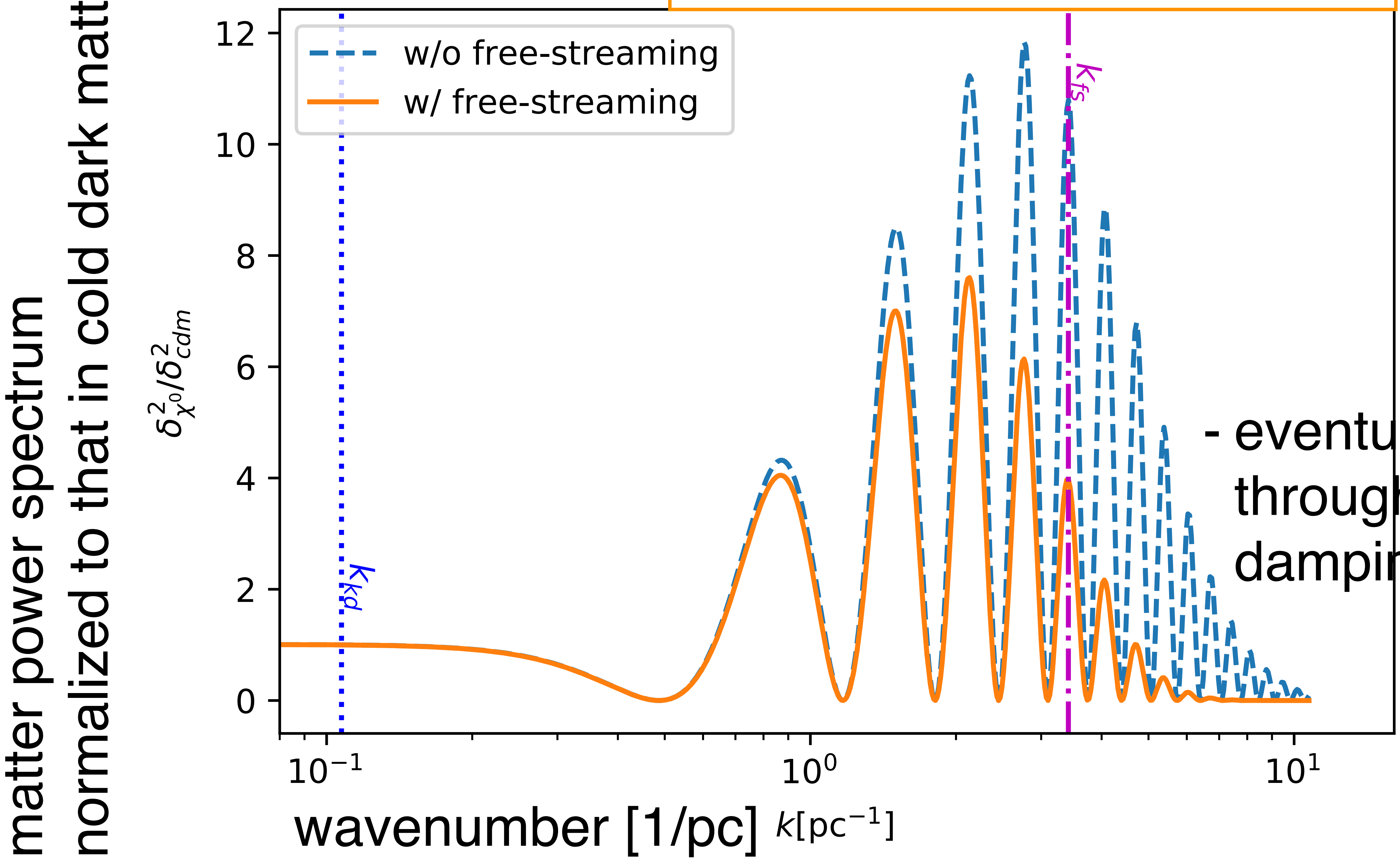
Bertschinger, PRD, 2006

sudden (gradual) decoupling → horizon scale at decoupling << (~) damping scale → enhanced (damped) dark acoustic oscillation

Power spectrum

Wino dark matter - inelastic scattering

AK, Sekiguchi, and Takahashi, arXiv:1901.09992



- eventually damped through Landau damping

Free-streaming after decoupling dominates damping

Boost factor

Wino (or generically electroweakino) dark matter

- annihilation into gauge bosons are non-perturbatively enhanced toward lower velocity (Sommerfeld enhancement)

Hisano, Matsumoto, and Nojiri, PRD, 2003

→ good target of indirect detection experiments

Hisano, Matsumoto, and Nojiri, PRL, 2004

...

Boost factor: $L(M) = (1+B(M))\bar{L}(M)$ - total luminosity

$\bar{L}(M)$ - contribution from coarse-grained distribution squared $\langle\rho\rangle^2$

$\langle\rho^2\rangle/\langle\rho\rangle^2 \geq 1$ $\langle\rho\rangle$ - e.g. Navarro-Frenk-White (NFW) profile

$B(M)$ - we estimate a subhalo contribution by using a halo model with extrapolations toward small scales

Strigari, Koushiappas, Bullock, and Kaplinghat, PRD, 2007

Kuhlen, Diemand, and Madau, ApJ, 2008

Boost factor

We adopt a halo model approach to estimate the boost factor with extrapolations

$$B(M) = \frac{1}{\bar{L}(M)} \int_{m_{\min}}^{M} dm \frac{dn_{\rm sub}}{dm} (1 + B_{\rm sub}(m)) \bar{L}_{\rm sub}(m)$$

$m_{\min}$: minimal halo mass

Hierarchical structure: $B = B_{\rm sub}$, $\bar{L} = \bar{L}_{\rm sub}$

Coarse-grained luminosity $\bar{L}$

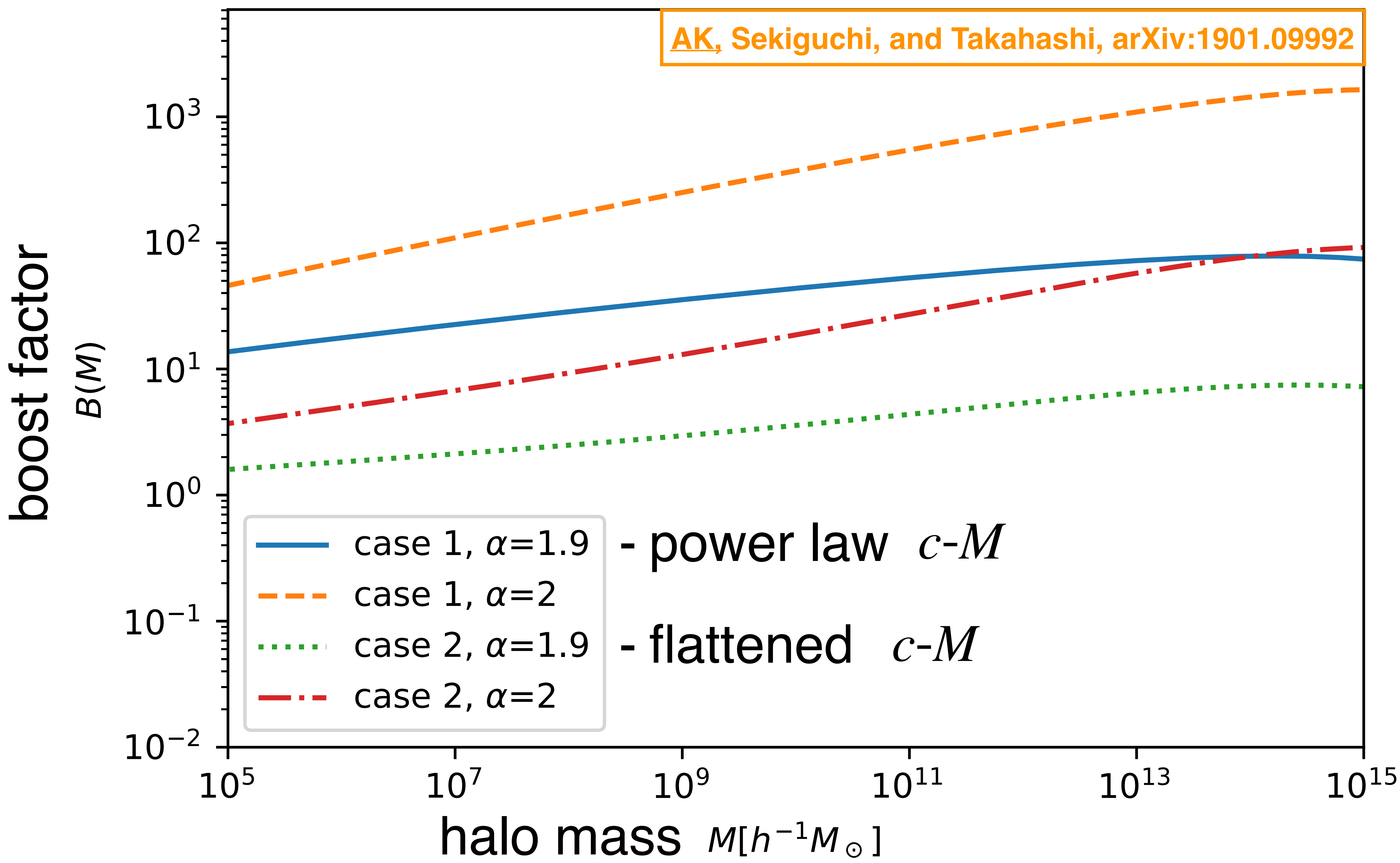
- Navarro-Frenk-White (NFW) profile c-M relation

power-law or flattened?

Subhalo mass function: $dn_{\rm sub}/dm$ power-law index $\alpha = 1.9\text{-}2.0$

$$\times \frac{(dn/d\ln M)_\chi}{(dn/d\ln M)_{\rm cdm}}\bigg|_{\rm PS}$$ for wino dark matter

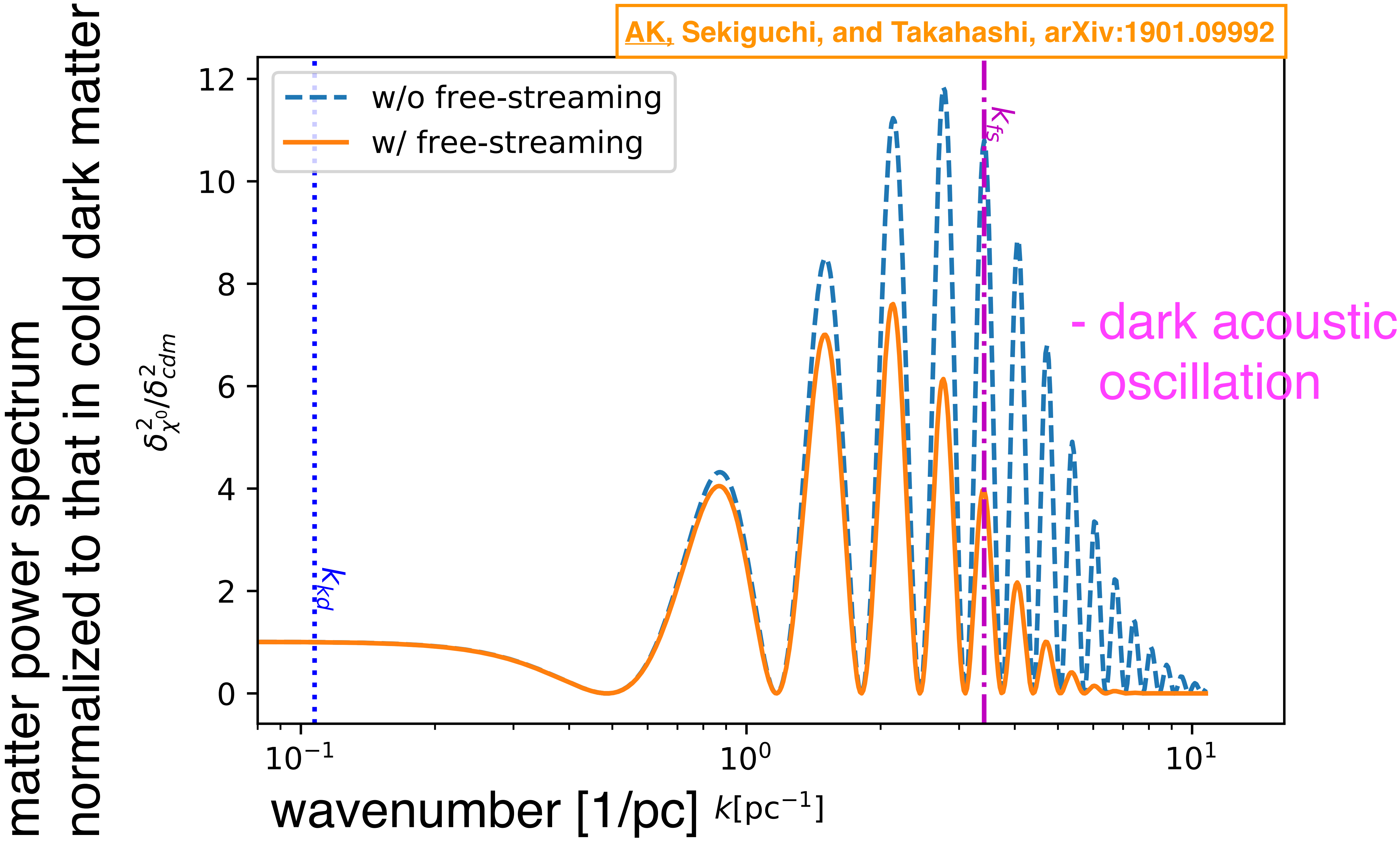
Estimated boost factor



Boost factor depends on power-law index of the subhalo mass function α and the c-M relation

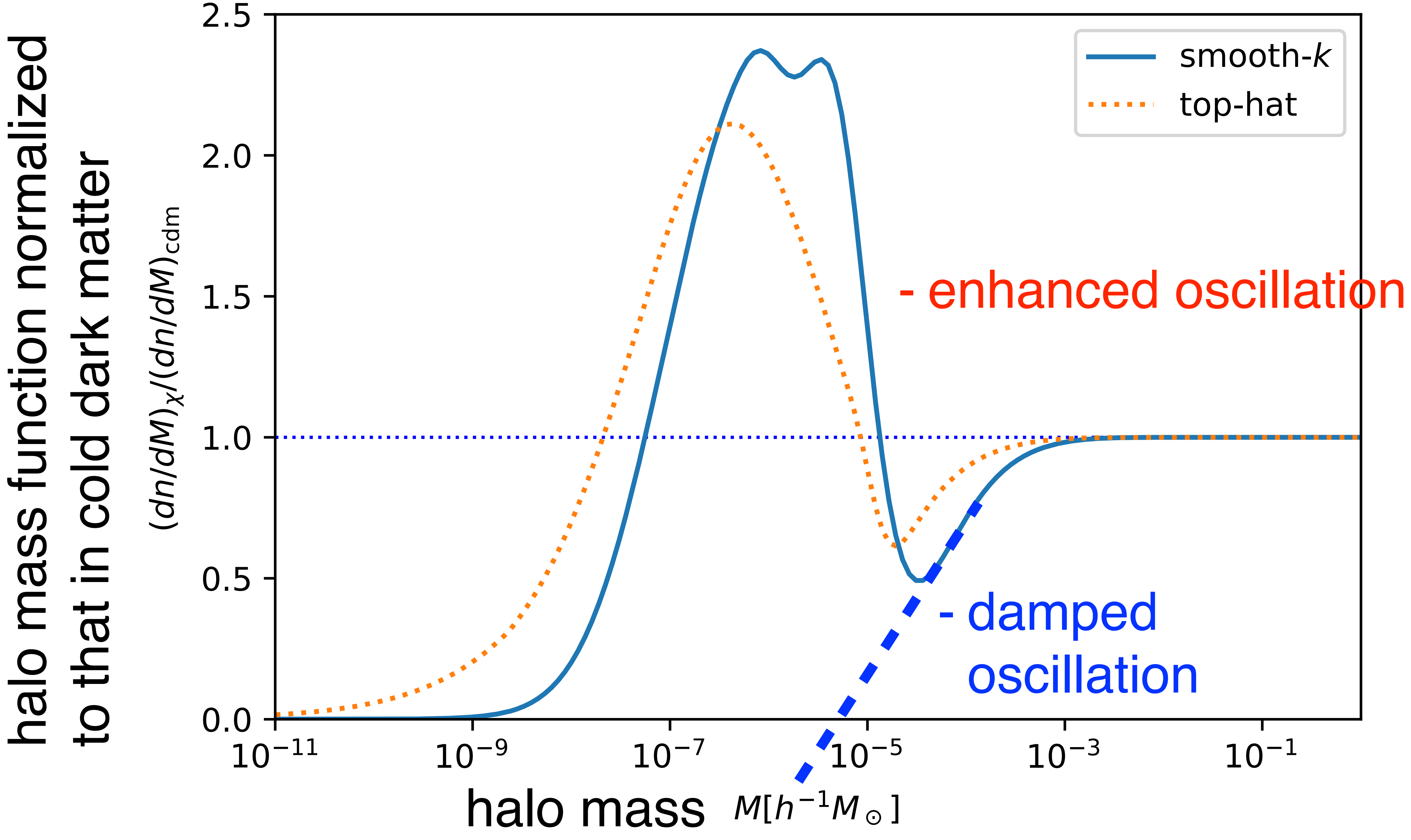
Power spectrum

Wino dark matter - inelastic scattering



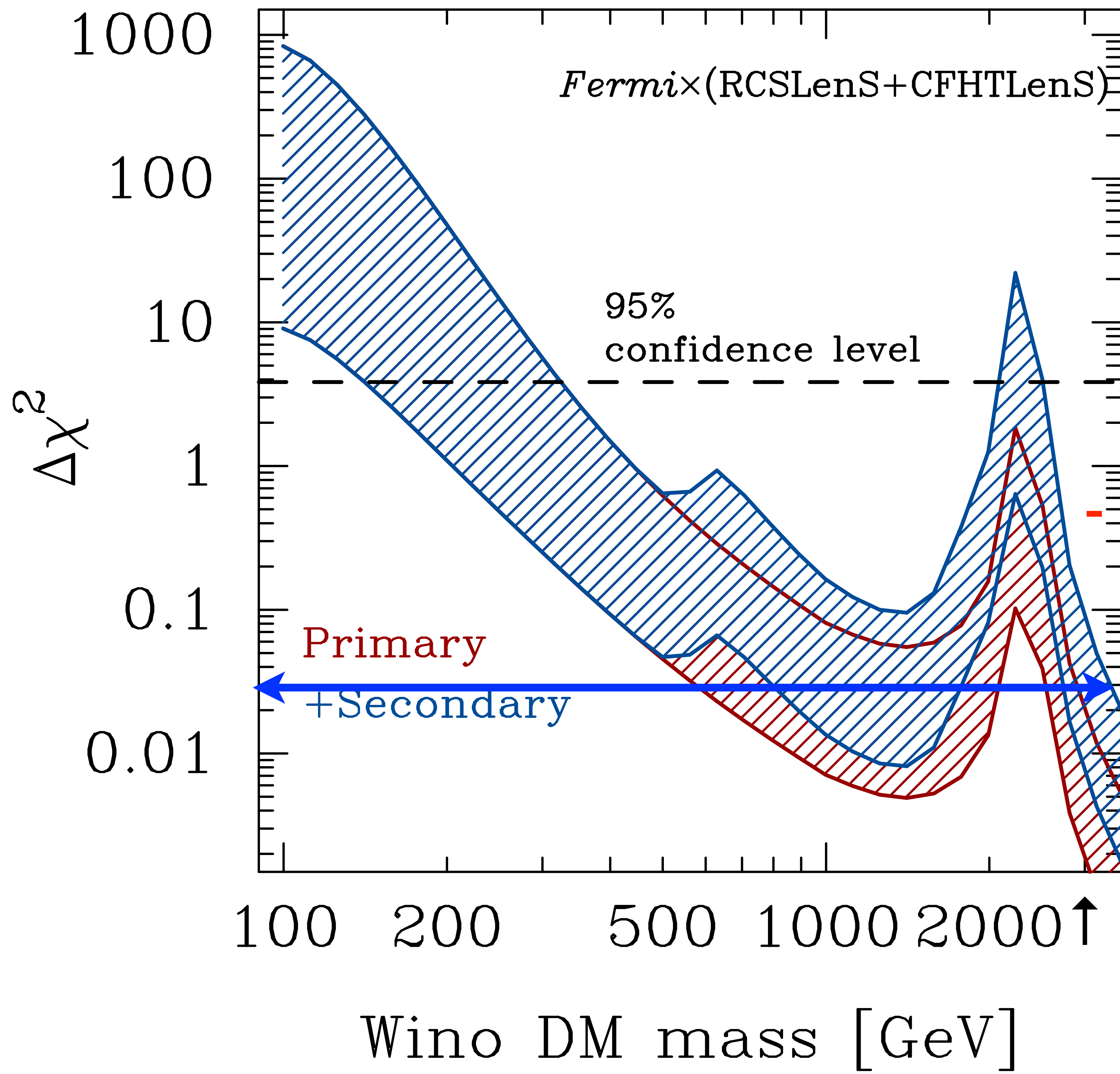
Powers at the pc scale are enhanced!: overshooting phenomenon

Estimated boost factor



Enhanced by a factor of 4.1 and 8.8 (1.5 and 2.9) with $\alpha = 1.9$ and 2.0 in case 1 (2) when compared to damped oscillation

Indirect detection



Enhanced abundance of Earth mass halos is not taken into account: to be updated!

- boost factor uncertainty

LSST-like survey

Shirasaki, Macias, Horiuchi, Shirai and Yoshida, PRD, 2016

↑ thermal wino $m_\chi \simeq 3\,\mathrm{TeV}$

Cross-correlation of gamma-ray background w/ large-scale structure (e.g., weak lensing) will enjoy statistical improvement in near future!

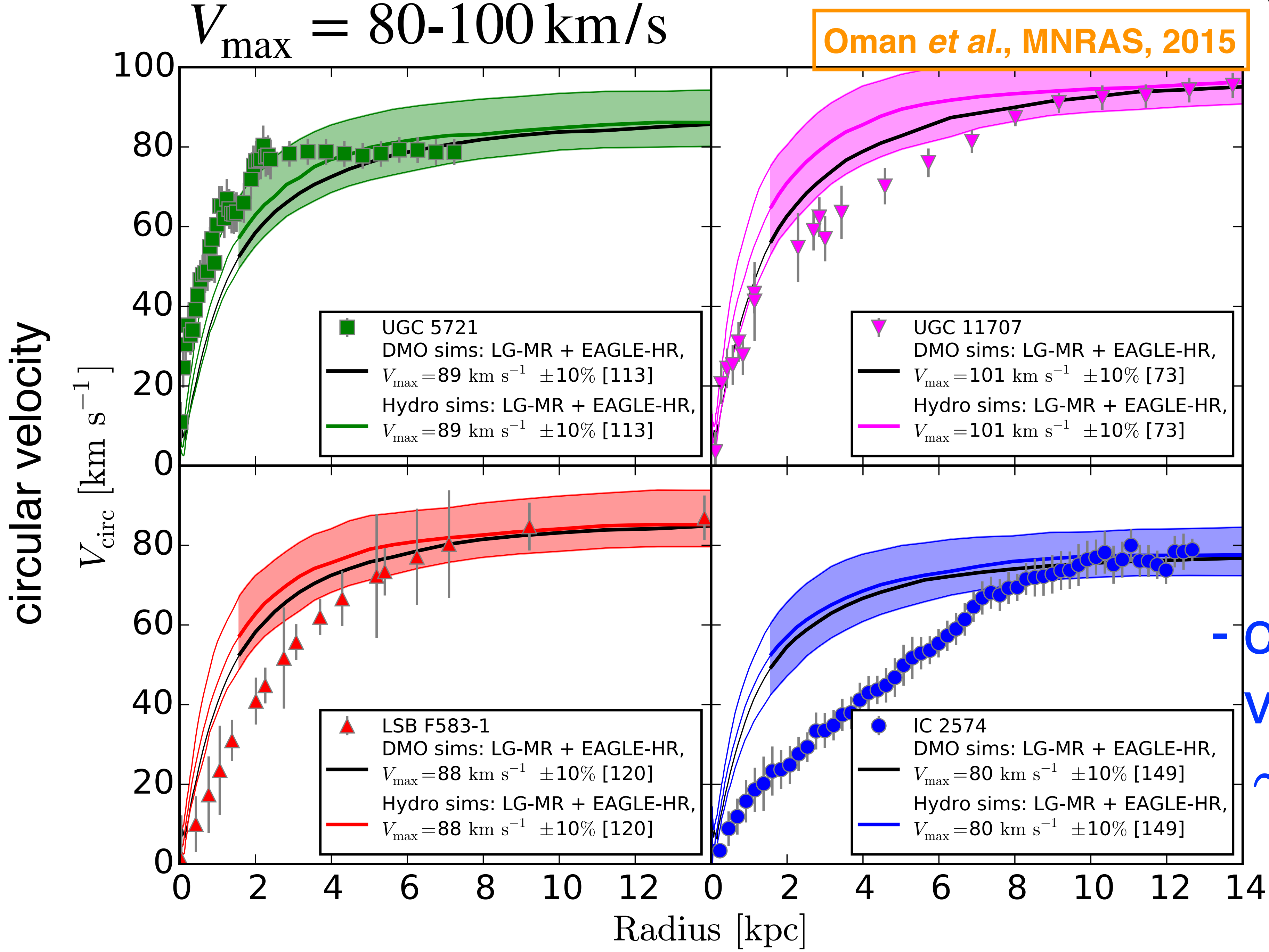
Small-scale issues

Diversity of inner rotation curves

Collisionless dark matter prediction: inner circular velocity is almost uniquely determined by outer circular velocity

↔ observations show diversity

$V_{\rm max} = 80\text{-}100\,{\rm km/s}$



✳ unique prediction is related with the concentration-mass relation

- overpredict the circular velocity by a factor of ∼ 2 (∼ 4 in mass)

Possible solutions

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

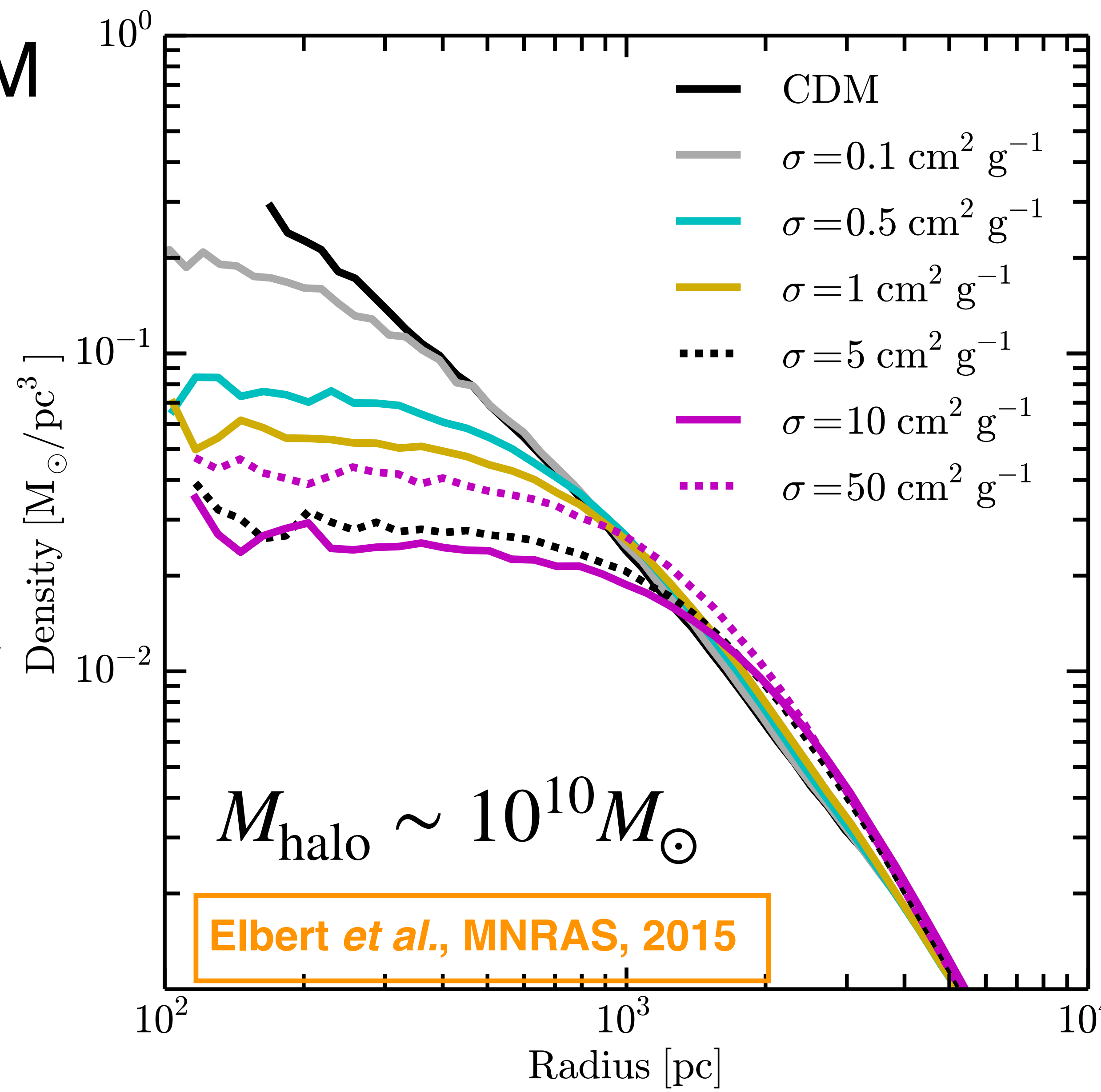
The issues may indicate alternatives to CDM (WIMPs)

- self-interacting dark matter: SIDM

$$\sigma/m = \mathcal{O}(1)\,\mathrm{cm}^2/\mathrm{g}$$

- reduce the central mass density

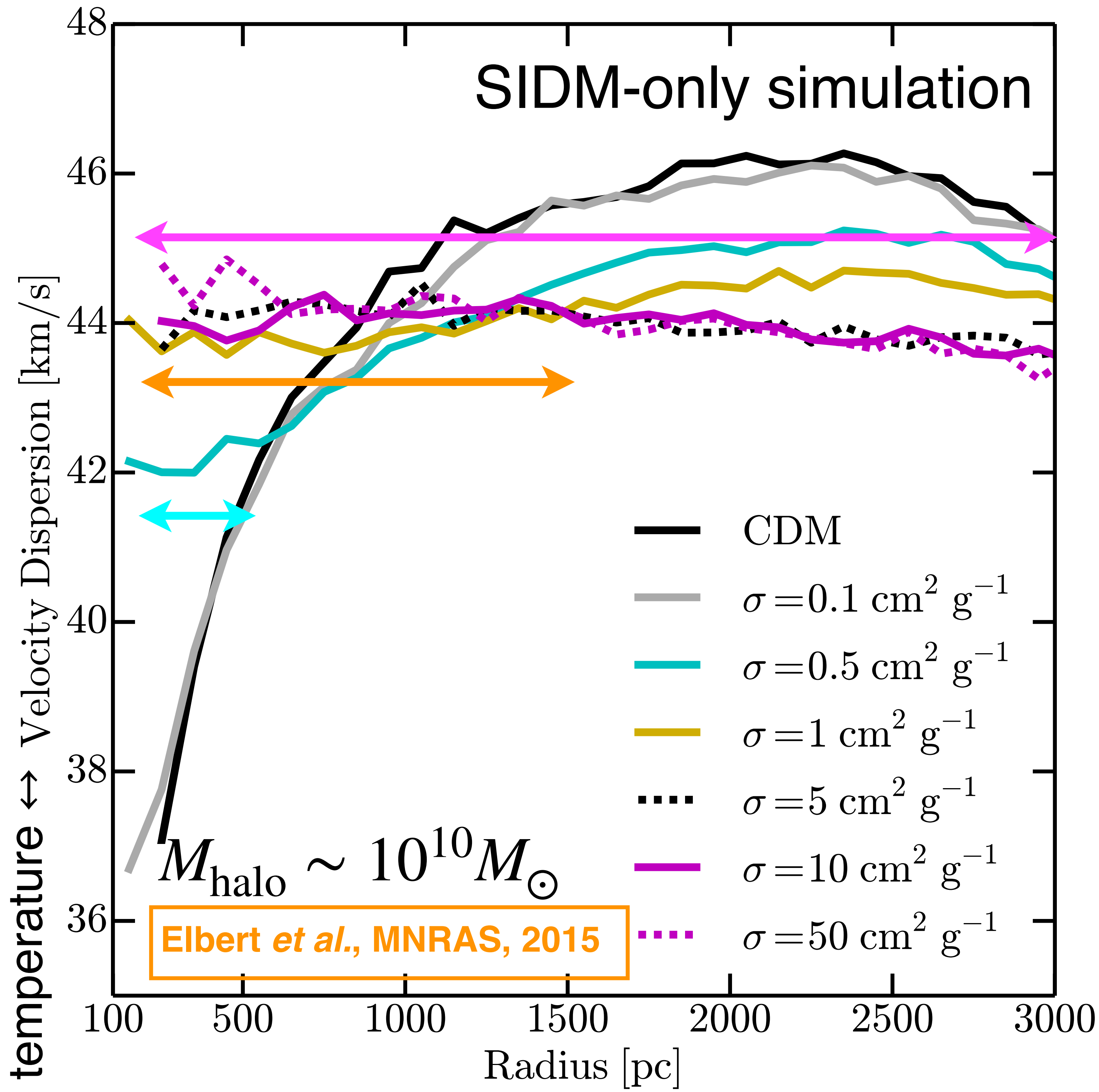
- ameliorate overprediction in some galaxies, but naively underpredict the circular velocity in other galaxies



Iso-thermal halo

Self-scattering leads to thermalization of DM halos at $r < r_1$
where self-scattering happens at least one time until now

$$\sigma/m\, \rho(r_1) v(r_1)\, t_{age} = 1$$



Key observation

Iso-thermal → Boltzmann distribution

$$\rho_{\rm DM}(\vec{x}) = \rho^0_{\rm DM} \exp(-\phi(\vec{x})/\sigma^2)$$

$$\Delta\phi = 4\pi G(\rho_{\rm DM} + \rho_{\rm baryon})$$

- inner profile is exponentially sensitive to baryon distribution

Baryons form complex objects, which show a large diversity

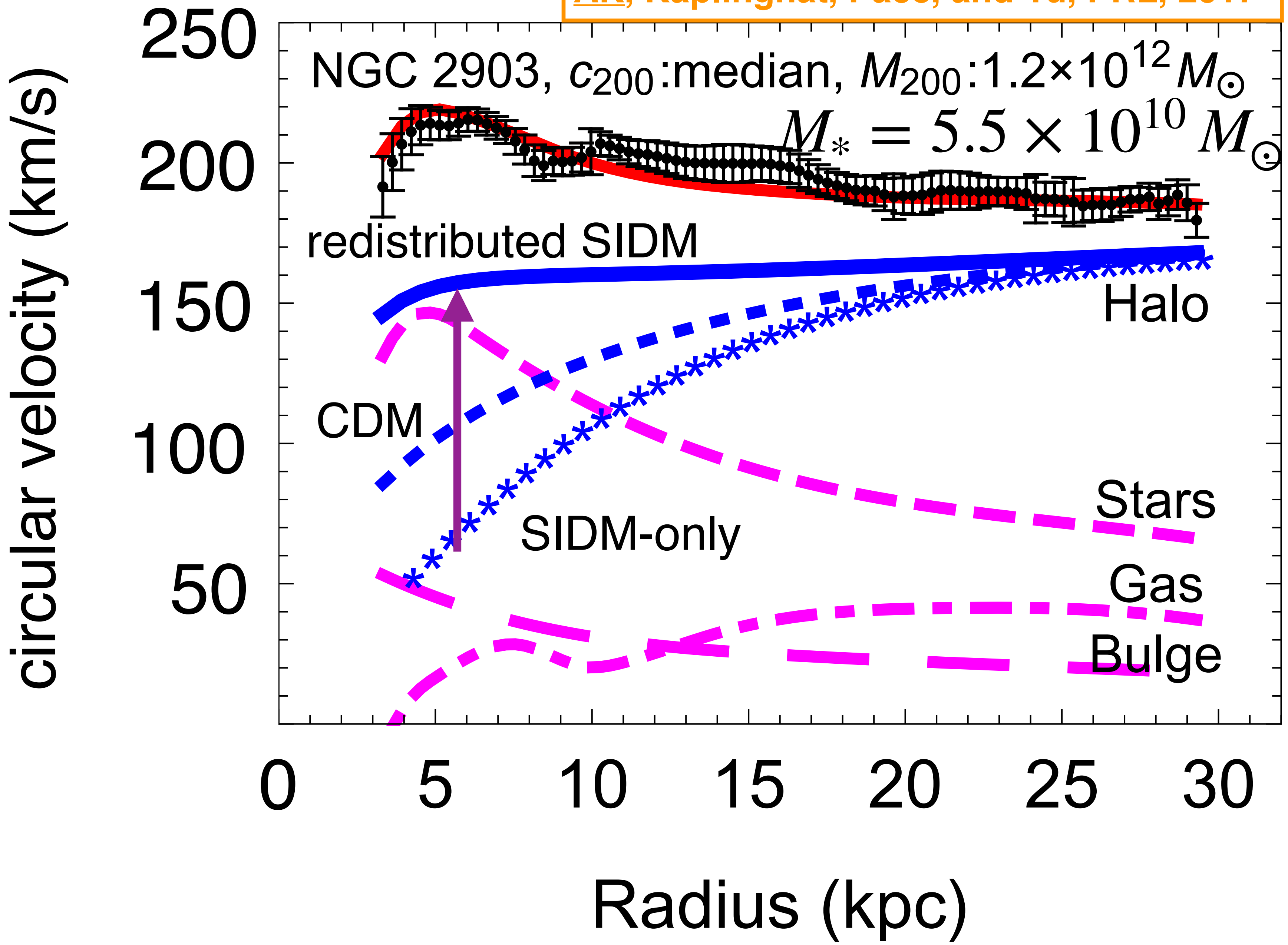
→ SIDM particles, redistributed according to formed baryonic objects, can show a diversity

✳ do not rely on unconstrained subgrid astrophysical processes take into account observed baryon distribution

Impacts in observed galaxies

$\ast$ Hereafter $\sigma/m = 3\,\mathrm{cm^2/g}$

AK, Kaplinghat, Pace, and Yu, PRL, 2017



- Observed stellar disk makes SIDM inner circular velocity ~ 3 times higher

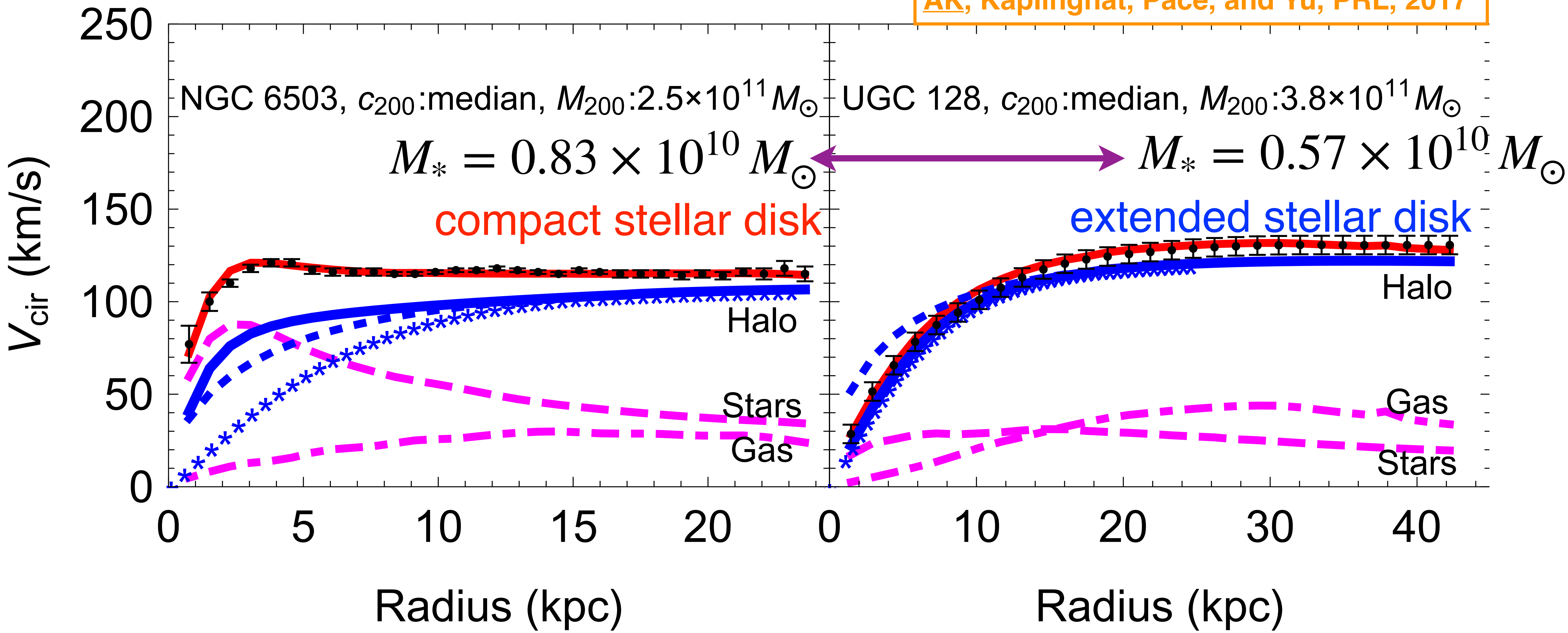
→ reproducing flat circular velocity at $10\text{-}20\,\mathrm{kpc}$

Diversity in stellar distribution

Similar outer circular velocity and stellar mass,
but different stellar distribution

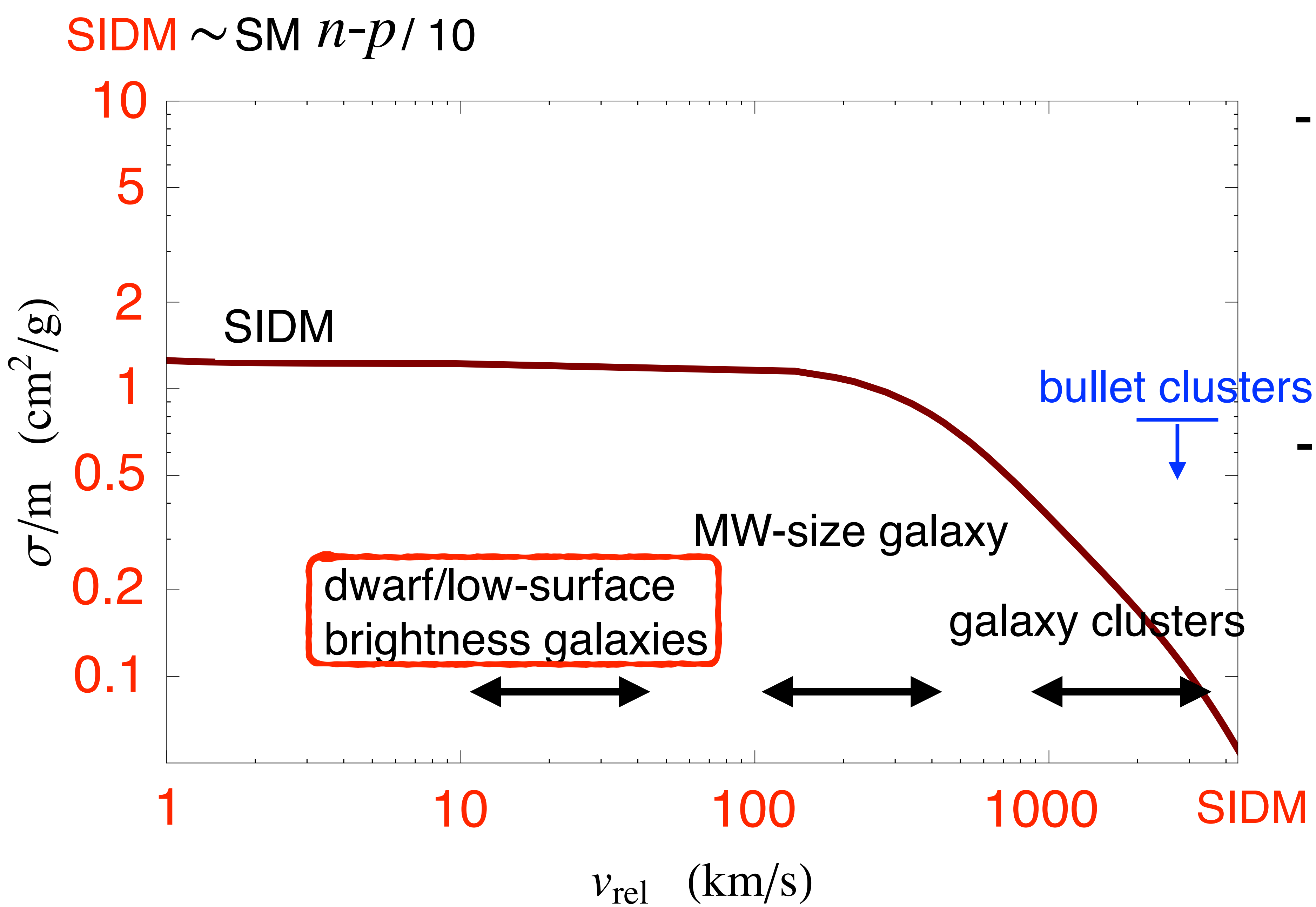
- compact → redistribute SIDM significantly
- extended → unchange SIDM distribution

AK, Kaplinghat, Pace, and Yu, PRL, 2017



Self-interacting dark matter

SIDM cross section indicated by small-scale puzzles



- cores in dwarf galaxies

  $\rightarrow \sigma/m \gtrsim 1\mathrm{cm}^2/\mathrm{g}$

- cores in galaxy clusters

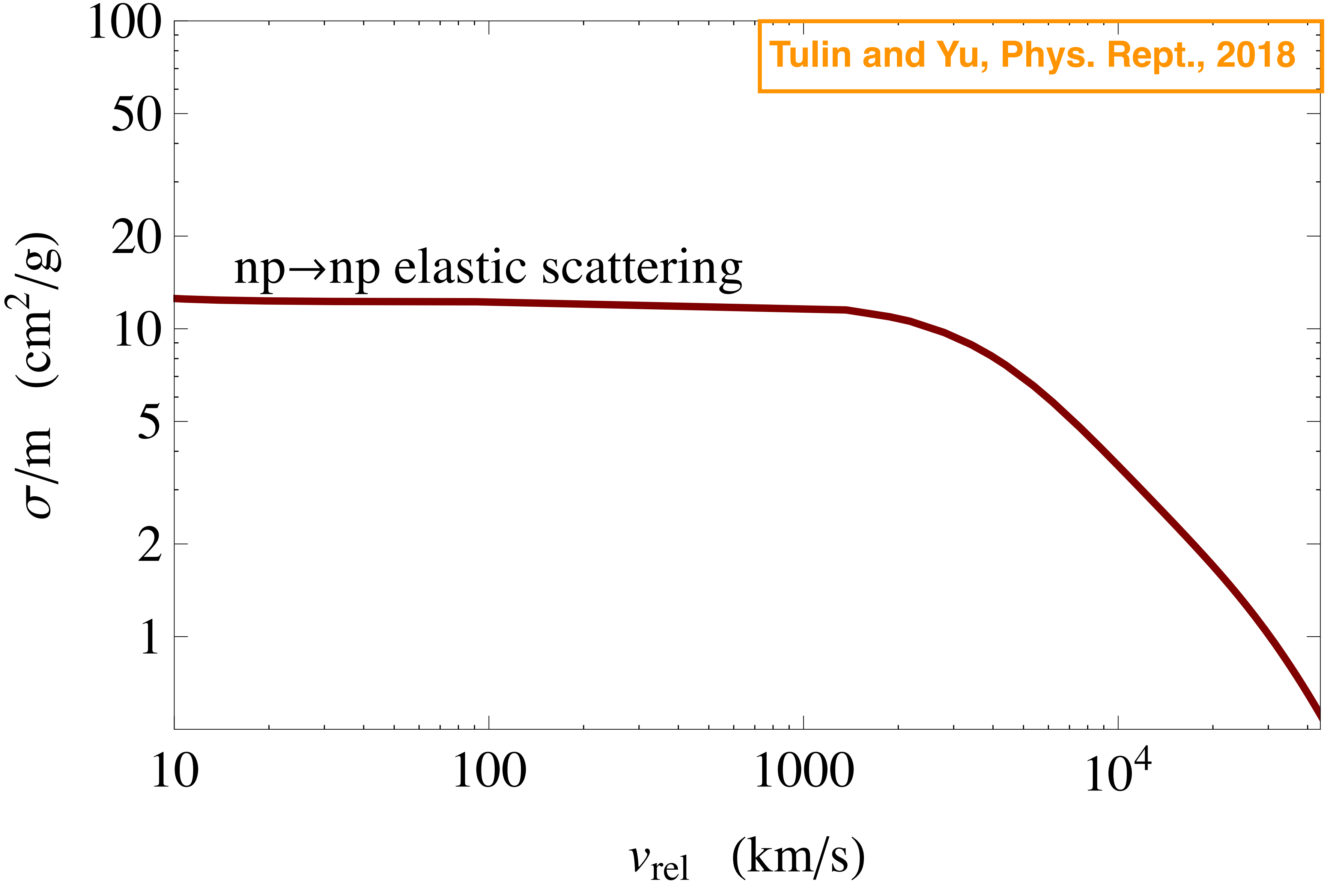
  $\rightarrow \sigma/m \sim 0.1\mathrm{cm}^2/\mathrm{g}$

Kaplinghat, Tulin, and Yu, PRL, 2016

Self-interacting dark matter

SM strong dynamics: nucleon elastic-scattering cross section

- diminishing w/ increasing velocity



Others

Long-lived over the age of the Universe

Weak-scale DM particle, $m_{\rm dm} = 100\,{\rm GeV}$, decays even through the gravitational interaction →$\tau \sim 16\pi\, m_{\rm pl}^2/m_{\rm DM}^3 \simeq 10\,{\rm yr}$ (↔$\tau_{\rm DM} > 10^{10}\,{\rm yr}$)

To stabilize the DM particle…

New symmetry

Proton p is long-lived ← baryon number conservation
conservation law ↔ symmetry though the Noether's theorem

Light particle

A keV-scale particle decays through the weak interaction
→ (marginal) $\tau \sim 64\pi^3/(G_{\rm F}^2 m_{\rm DM}^5) \simeq 10^{11}\,{\rm yr}$

+

Feeble interaction

A keV-scale particle decays through the gravitational interaction
→ $\tau \simeq 10^{25}\,{\rm yr}$

Classification of DM candidates as a temporal summary

candidate	stability	interaction
WIMP (neutralino)	symmetry (R-parity)	weak
light FIMP (light gravitino, moduli)	light + feeble interaction	feeble

New symmetry

Minimal phenomenological approach:
introducing a new Z_2-symmetry under which
the SM particles are *even*, while a DM particle is *odd*

➡ Interaction strength is not constrained

Origin?

Baryon number conservation
was understood
as an *accidental symmetry*
a half century after the discovery

electron (e) discovery
(1897, Thomson)
proton (p) discovery
(1919, Rutherford)

theoretical and experimental progress ⬇

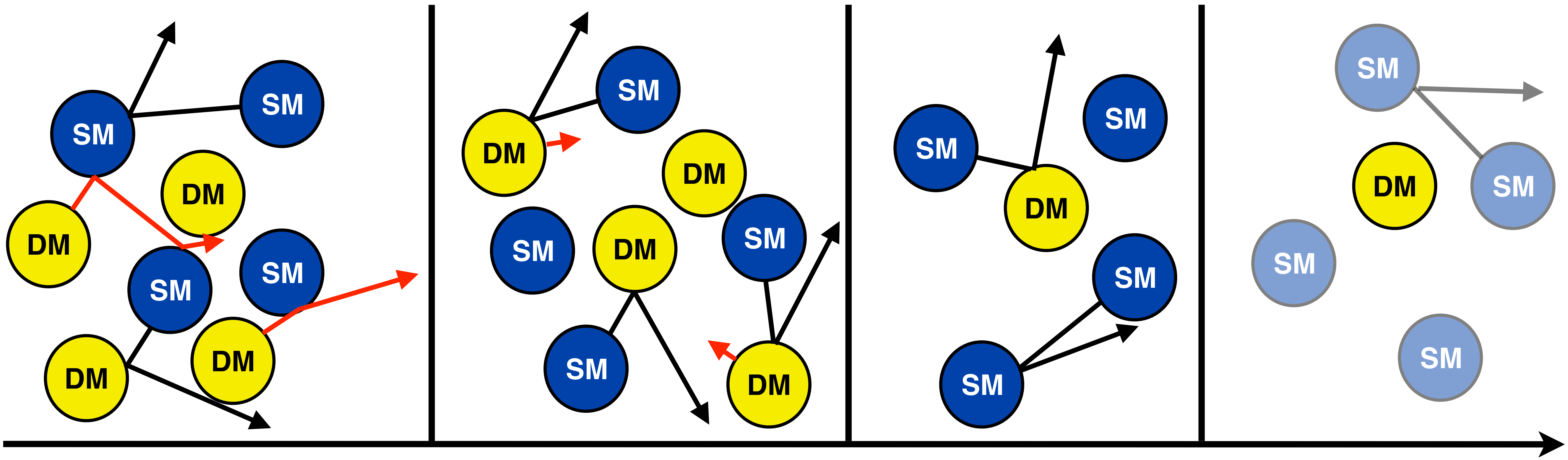
Electroweak theory
(1961, Grashow)
(1967, Weinberg)
(1968, Salam)

Caveat?

Quantum gravity violates any global
symmetry?

Kallosh *et al.*, PRD, 1995

Summary of thermal history of WIMPs



early Universe

$T \sim m_{\rm dm}$

chemical freeze-out
$\leftrightarrow$ ~~annihilation~~

kinetic decoupling
$\leftrightarrow$ ~~elastic scattering~~

late Universe

→ **CDM**

Long-lived over the age of the Universe

Weak-scale DM particle, $m_{\rm dm} = 100\,{\rm GeV}$, decays even through the gravitational interaction →$\tau \sim 16\pi\, m_{\rm pl}^2/m_{\rm DM}^3 \simeq 10\,{\rm yr}$ (↔$\tau_{\rm DM} > 10^{10}\,{\rm yr}$)

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+

Feeble interaction

A keV-scale particle decays through the gravitational interaction
→ $\tau \simeq 10^{25}\,{\rm yr}$

Light particle

Light particles are excluded by collider experiments unless they are hardly produced

→ **Light particle** + **Feeble interaction**

Feebly Interacting Massive Particle (FIMP)

Gauge-mediated SUSY breaking (GMSB)
masses of sparticles: $m_{\rm SUSY} \sim (\alpha/4\pi) F/M_{\rm med} \sim 1\,{\rm TeV}$
$\sqrt{F} \sim M_{\rm med} \leftrightarrow \sqrt{F} \sim 10^5\,{\rm GeV}$
→ gravitino mass: $m_{3/2} \sim F/m_{\rm pl} \sim 10\,{\rm eV}$
coupling: $m_{\rm SUSY}/F \sim 1/(10^7\,{\rm GeV})$

Moduli field, which determines the size or shape of the extra-dimension space in the superstring theory, is also a typical example.

Light particle + **Feeble interaction**

Feeble interaction
→ DM particles decouple from SM particles in the very early Universe: $T > m_{\rm dm}$
→ DM particles are not thermalized throughout the thermal history of the Universe

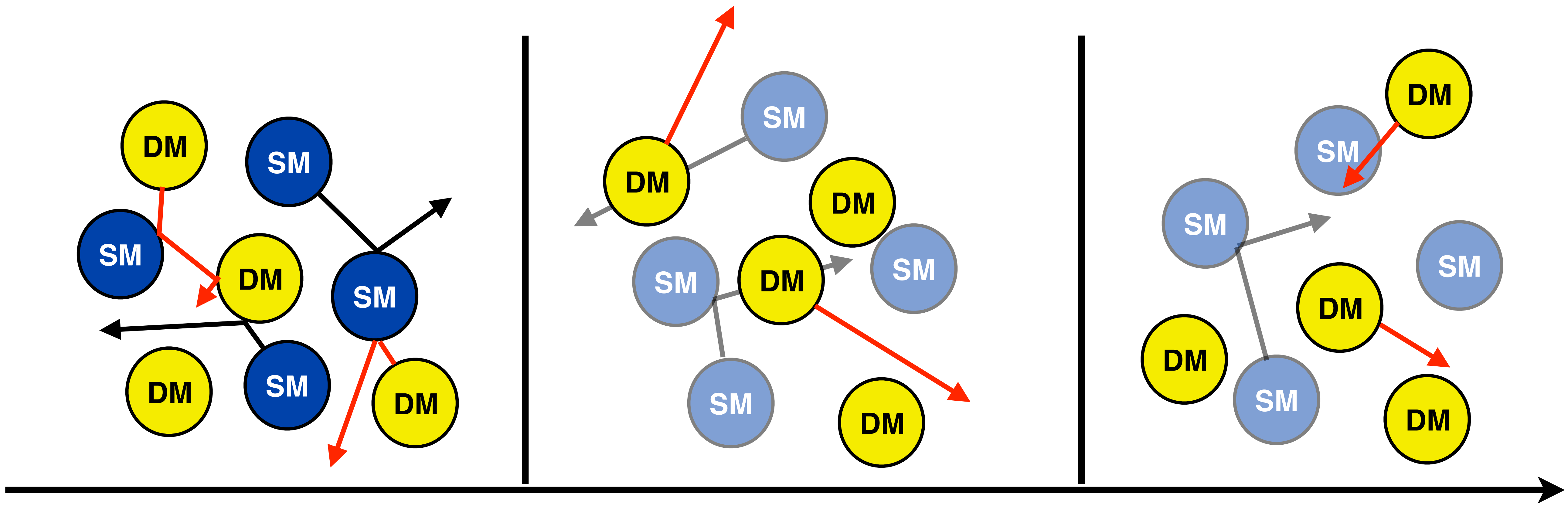
A variety of production mechanisms

Early decoupling

Non-thermal production

Coherent oscillation as a Bose-Einstein condensate

Thermal history of early decoupled DM



early Universe

thermal decoupling

$T \sim m_{\rm dm}$

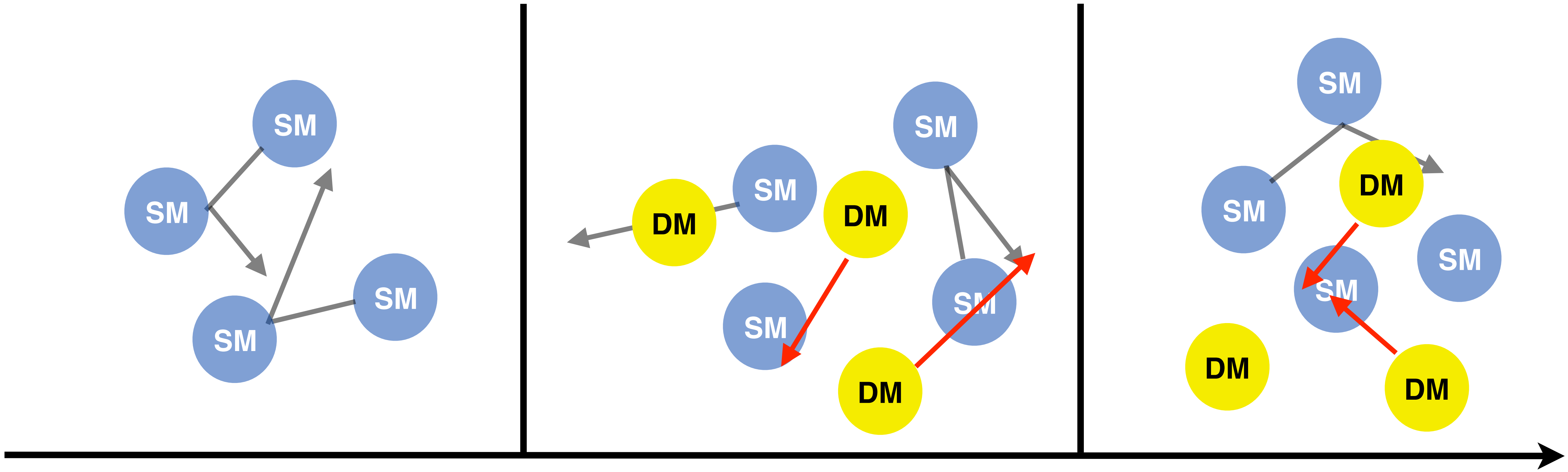
late Universe

start to free-stream at the speed of light

eV-scale mass
→ becomes non-relativistic only around the matter-radiation equality

➡ **HDM** ⬌ **cannot account for the whole DM**

Thermal history of non-thermal produce DM



early Universe

non-thermal production

$T \sim m_{\rm dm}$

late Universe

never in thermal equilibrium with SM particles

The DM mass can be larger than the early decoupling case

➡ **HDM/WDM/CDM**

Classification of DM candidates as a temporal summary

candidate	stability	interaction	production mechanism (warmness)
WIMP (neutralino)	symmetry (R-parity)	weak	thermal freeze-out (cold)
light gravitino	light + feeble interaction (R-parity)	feeble	early decoupling (hot)
sterile neutrino	light + feeble interaction	feeble	non-thermal (hot/warm/cold)
moduli, QCD axion	light + feeble interaction	feeble	coherent oscillation (cold)

Coherent oscillation as a Bose-Einstein condensate

Bosonic DM can have a large occupation number in one state
→ a coherent (classical) condensate follows the equation of motion of the field

DM in a form of a field → **CDM**

1. an initial field value is displaced from the origin, for instance, by inflation dynamics: $\phi = \phi_0$
2. start to oscillate around the origin at $H \sim m_\phi$
3. energy density redshifts as matter: $\rho_\phi \propto (1+z)^3$

initial field value should be elaborated

$$\Omega_\phi h^2 \simeq 0.6 \times \left(\frac{m_\phi}{\mathrm{keV}}\right)^{1/2} \left(\frac{\phi_0}{10^{11}\,\mathrm{GeV}}\right)^2 \left(\frac{g_*}{100}\right)^{-1/4}$$