Dark matter in split supersymmetry: thermal wino dark matter and beyond

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Based on
AK, Toyokazu Sekiguchi, and Tomo Takahashi, arXiv:1901.09992
Masahiro Ibe, AK, Shin Kobayashi, and Wakutaka Nakano, JHEP, 2018
Masahiro Ibe, AK, Shin Kobayashi, Takumi Kuwahara, and Wakutaka Nakano, JHEP, 2019

June 3, 2019 @ JHU workshop

Hai-bo cannot make it…

Composite asymmetric dark matter and galactic rotation curves

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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 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: 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

Supersymmetry

Theory is invariant under boson ↔ fermion

Theoretical properties

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

Phenomenological (MSSM) properties

- SUSY breaking → Higgs potential
  - electroweak-scale SUSY → hierarchy problem
- provide a dark matter candidate $R\text{-parity} = (-1)^{3(B-L)+2s}$
- precise grand unification of gauge couplings

No naturalness…

LHC discovery of 125 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…

- new theoretical reasoning for WIMP?
    - Mini-split SUSY
        - sfermions > 100 TeV; gauginos ~ TeV
            - 125 GeV Higgs
            - dark matter
            - precise grand unification

- observational hints: small-scale issues in structure formation?

What I will discuss

What about others? What if WIMPs are subdominant?

Puzzles for WIMPs in structure formation — part 1

- diversity of rotation curves
- self-interacting dark matter $\sigma/m = \mathcal{O}(1)\,\mathrm{cm}^2/\mathrm{g} = \mathcal{O}(1)\,\mathrm{barn}/\mathrm{GeV}$

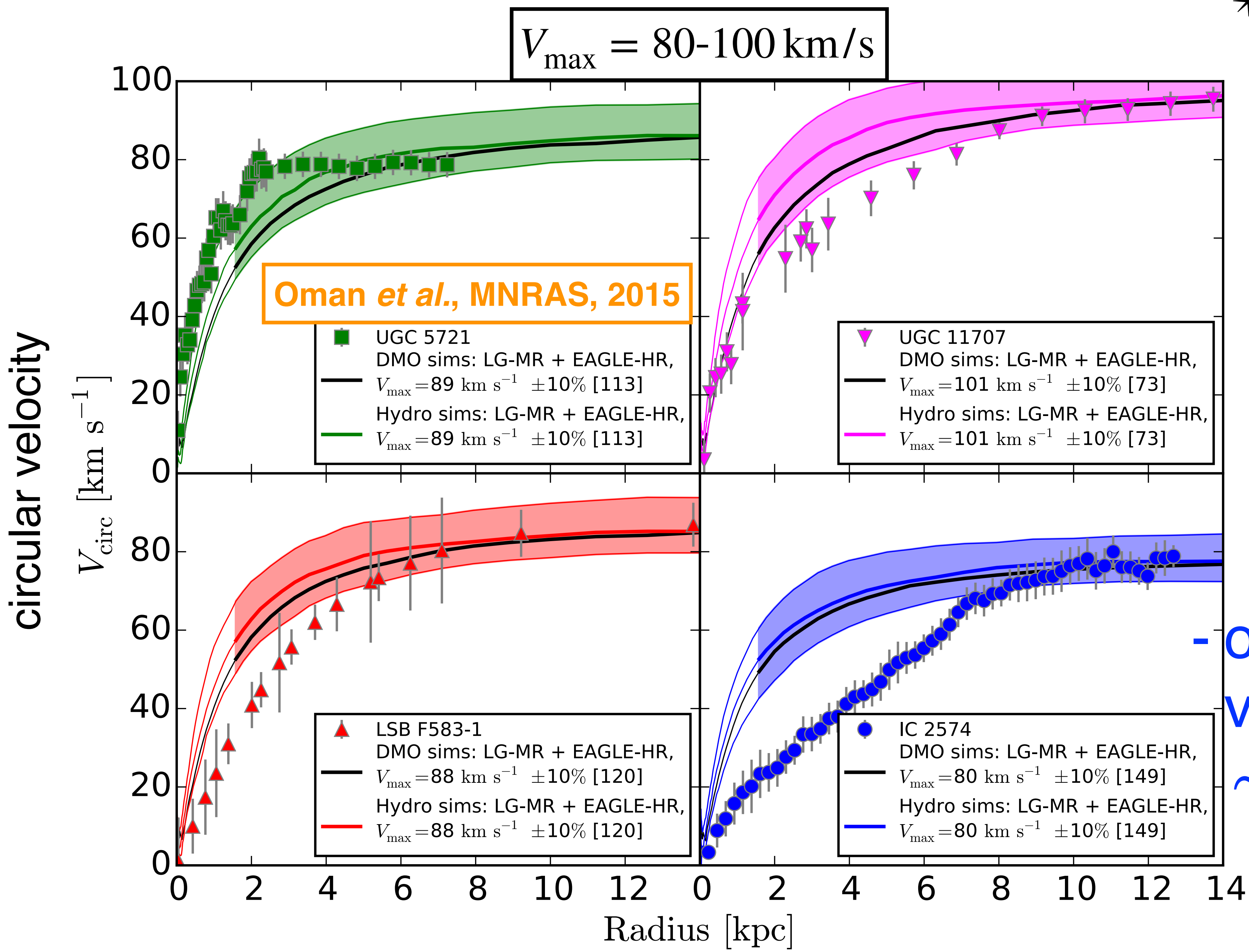
Composite asymmetric dark matter — part 2

- naturally realize self-interacting dark matter
- simple model → ultraviolet completion

Part 1: Diversity of inner rotation curves

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

↔ observations show diversity



✳ 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)

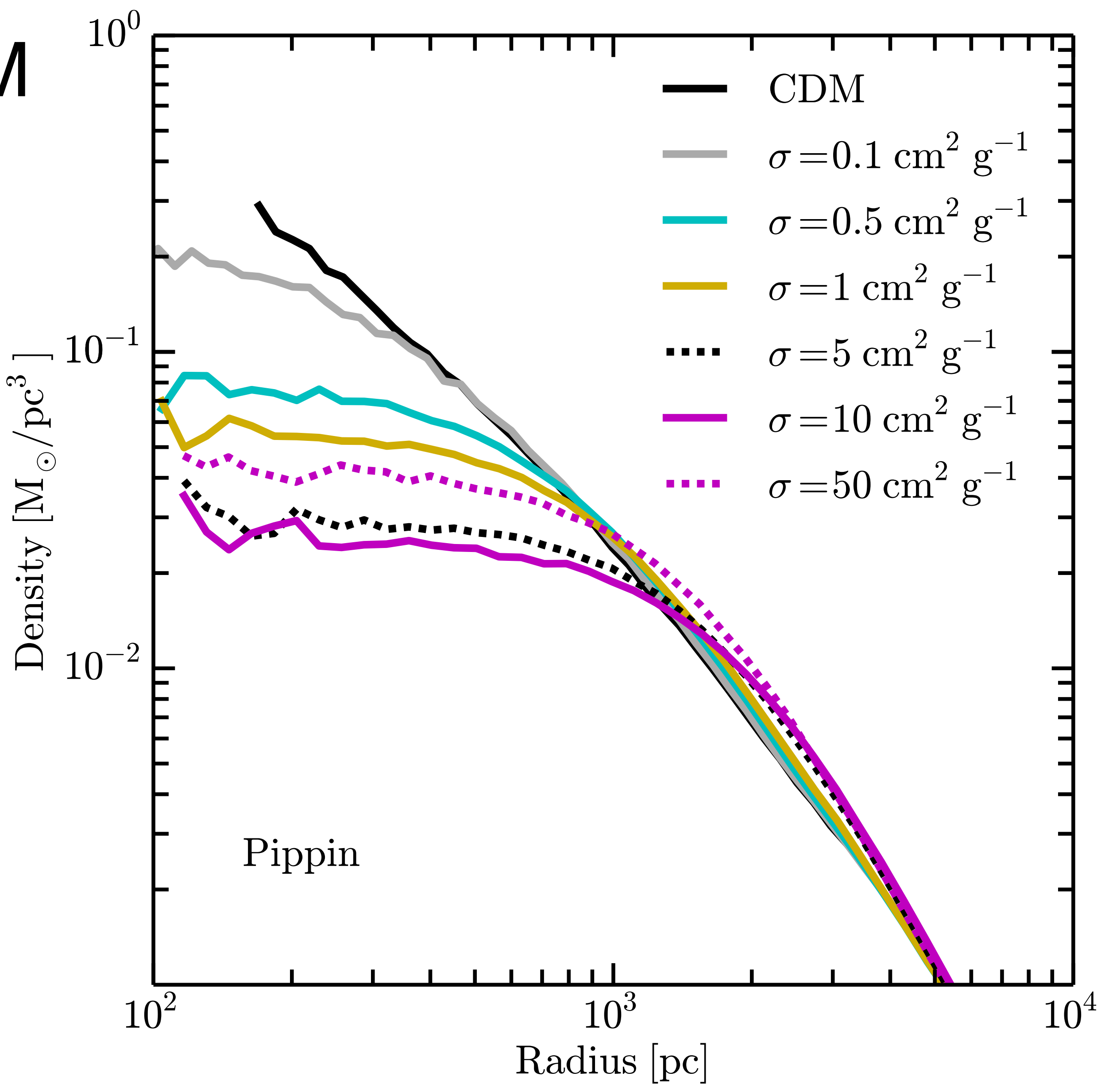
The issues may indicate alternatives to CDM (WIMPs)

- self-interacting dark matter: SIDM

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

- reduce the central mass density

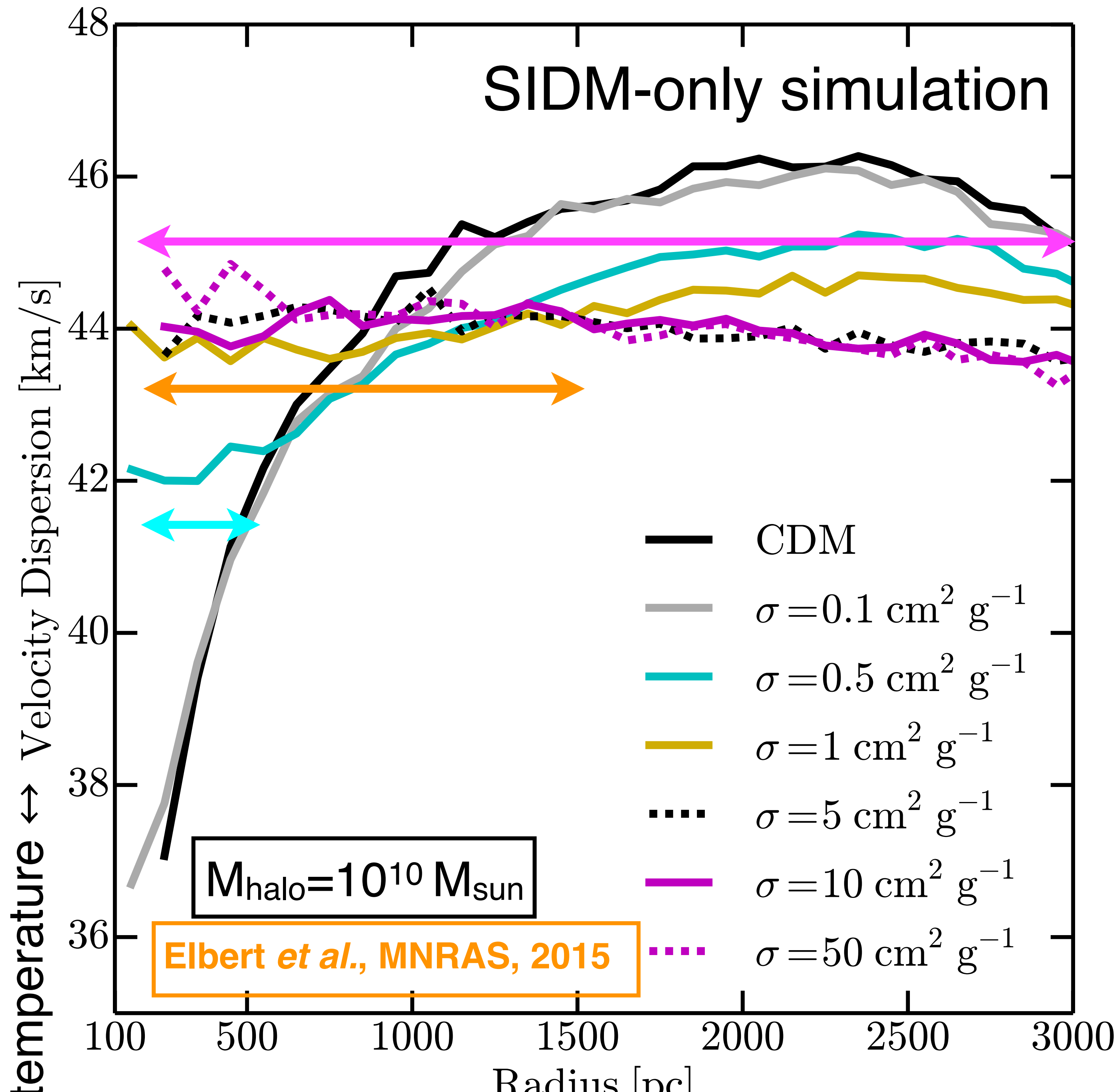
- ameliorate overprediction in some galaxies, but naively underpredict the circular velocity in other galaxies



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

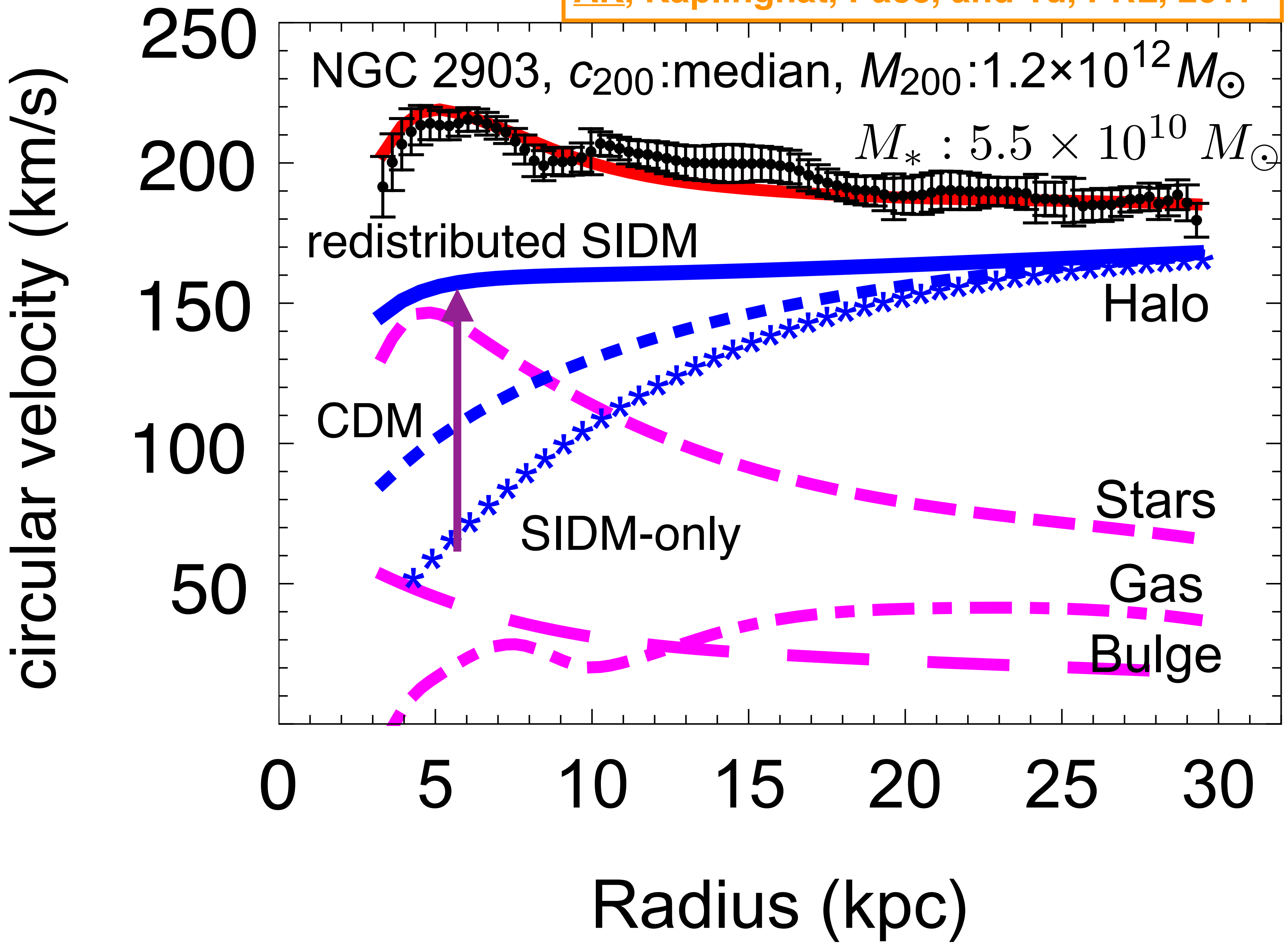
Baryons form complex objects, which show a large diversity

→ 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

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



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

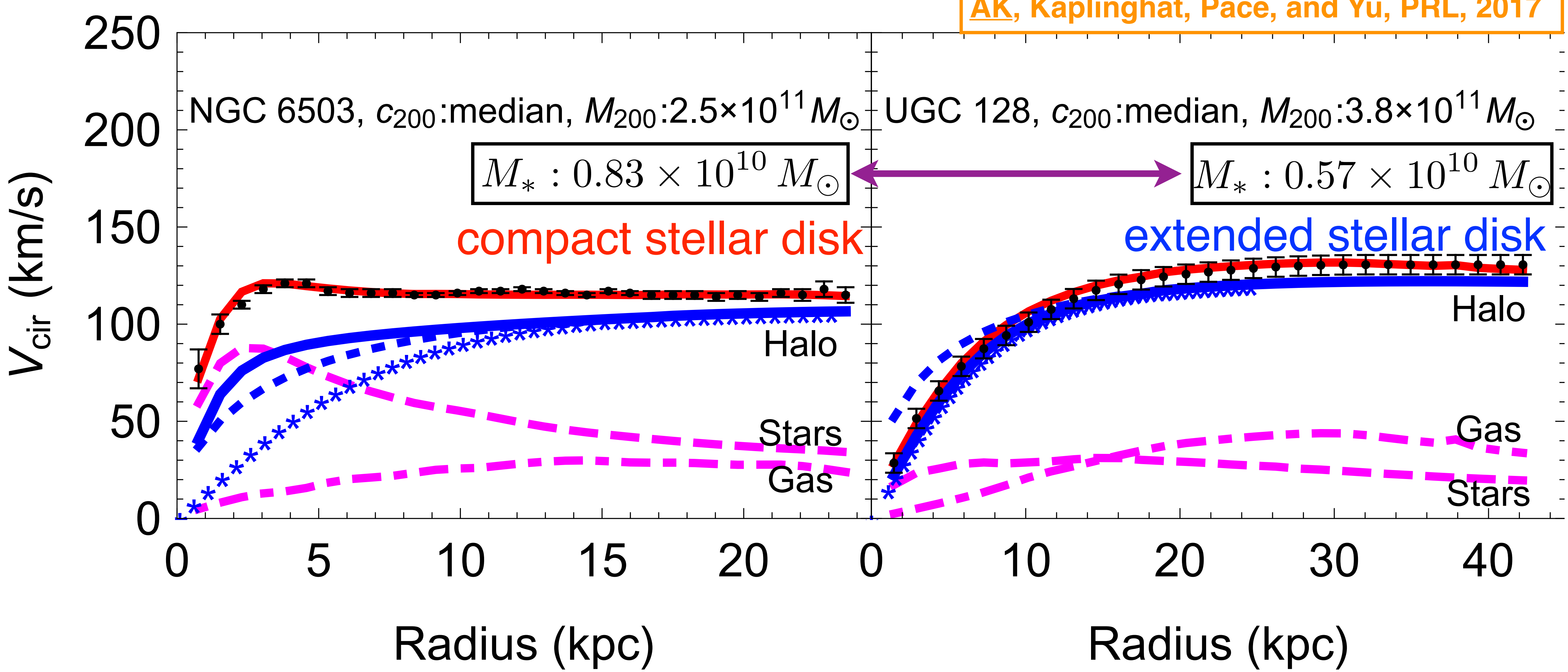
→ reproducing flat circular velocity at 10-20 kpc

Diversity in stellar distribution

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

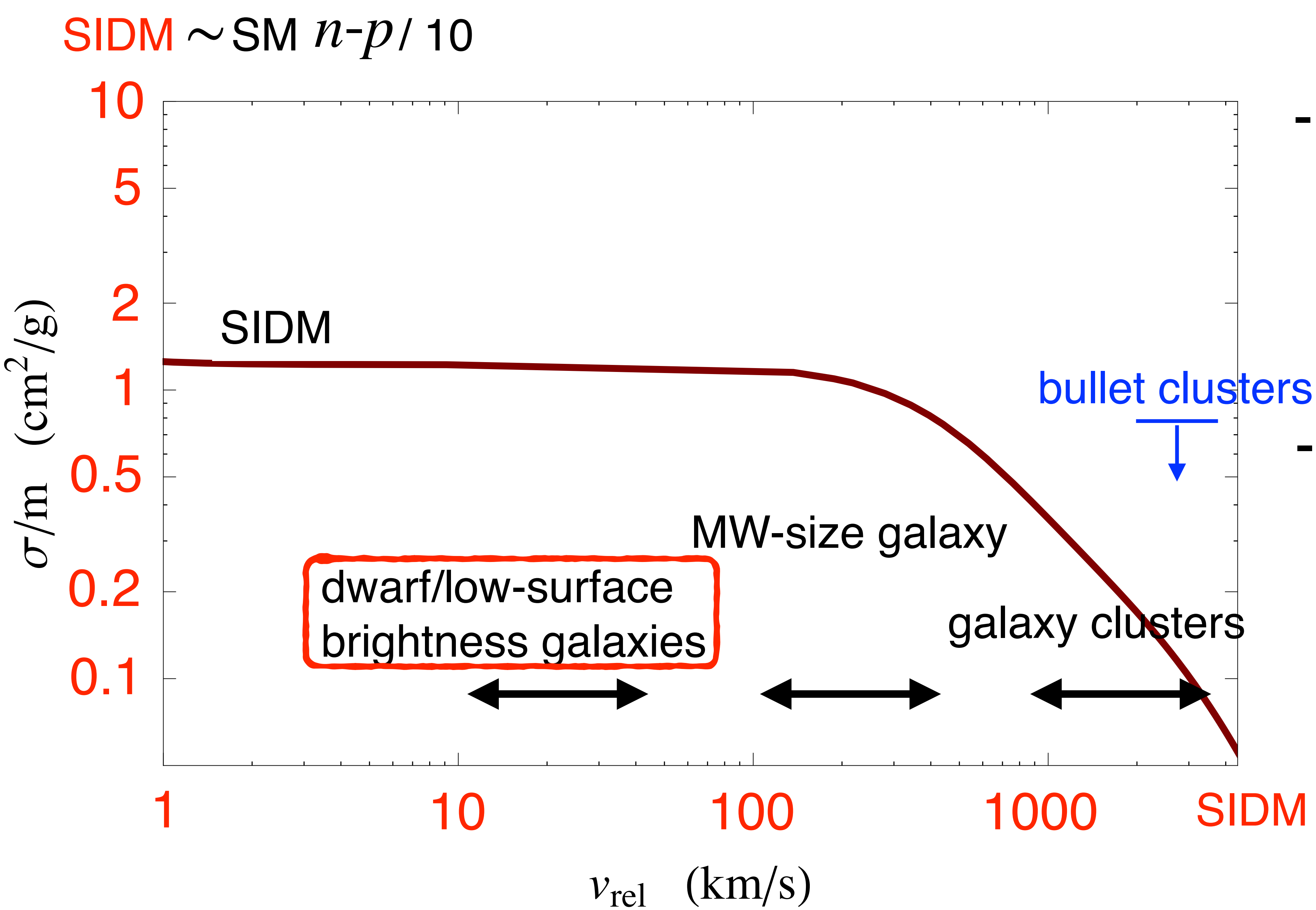
- compact → redistribute SIDM significantly
- extended → unchange SIDM distribution

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



Self-interacting dark matter

SIDM cross section indicated by small-scale puzzles



SIDM ~SM n-p / 10

- cores in dwarf galaxies

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

- cores in galaxy clusters

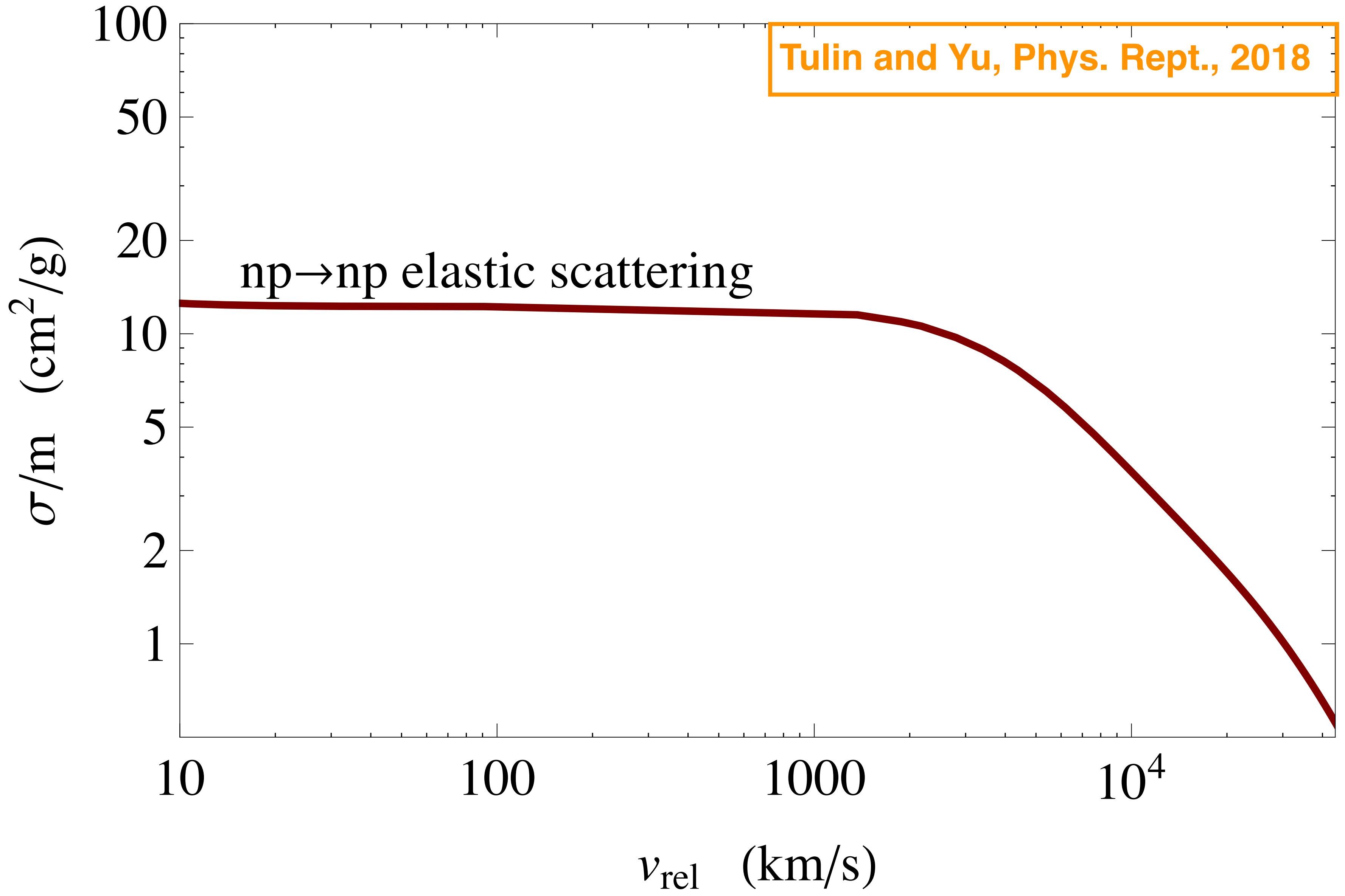
  → $\sigma/m \sim 0.1\mathrm{cm}^2/\mathrm{g}$

Kaplinghat, Tulin, and Yu, PRL, 2016

Self-interacting dark matter

SM strong dynamics: nucleon elastic-scattering cross section

- diminishing w/ increasing velocity



Part 2: 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 $\Lambda_{\rm QCD'}/M_* \ll 1$
- B' number asymmetry - cogenesis

Portal operator

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

$\ast$ when no particle charged under both gauge groups

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

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

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

- close to SM QCD dynamical scale

Thermal history

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

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

SM

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

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 nucleons into pions

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

dark

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

QCD' phase transition

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

pair annihilation of nucleon's

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

To be answered

Origin of the portal operator? - high-energy

- if $\frac{1}{M_*^n}\mathcal{O}_{\rm SM}\mathcal{O}_D$ and $\frac{1}{M_*^n}\mathcal{O}_{\rm SM}\overline{\mathcal{O}}_D$ coexist, asymmetry is not left

Asymmetry generation?

Fukugita and Yanagida, PLB, 1986

- compatible with, e.g., thermal leptogenesis?

Where is dark sector entropy gone? - low-energy

- $\Delta N_{\rm eff}$ from the dark sector (e.g., dark pions)

Simple model

Ibe, AK, Kobayashi, and Nakano, JHEP 2018

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

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

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

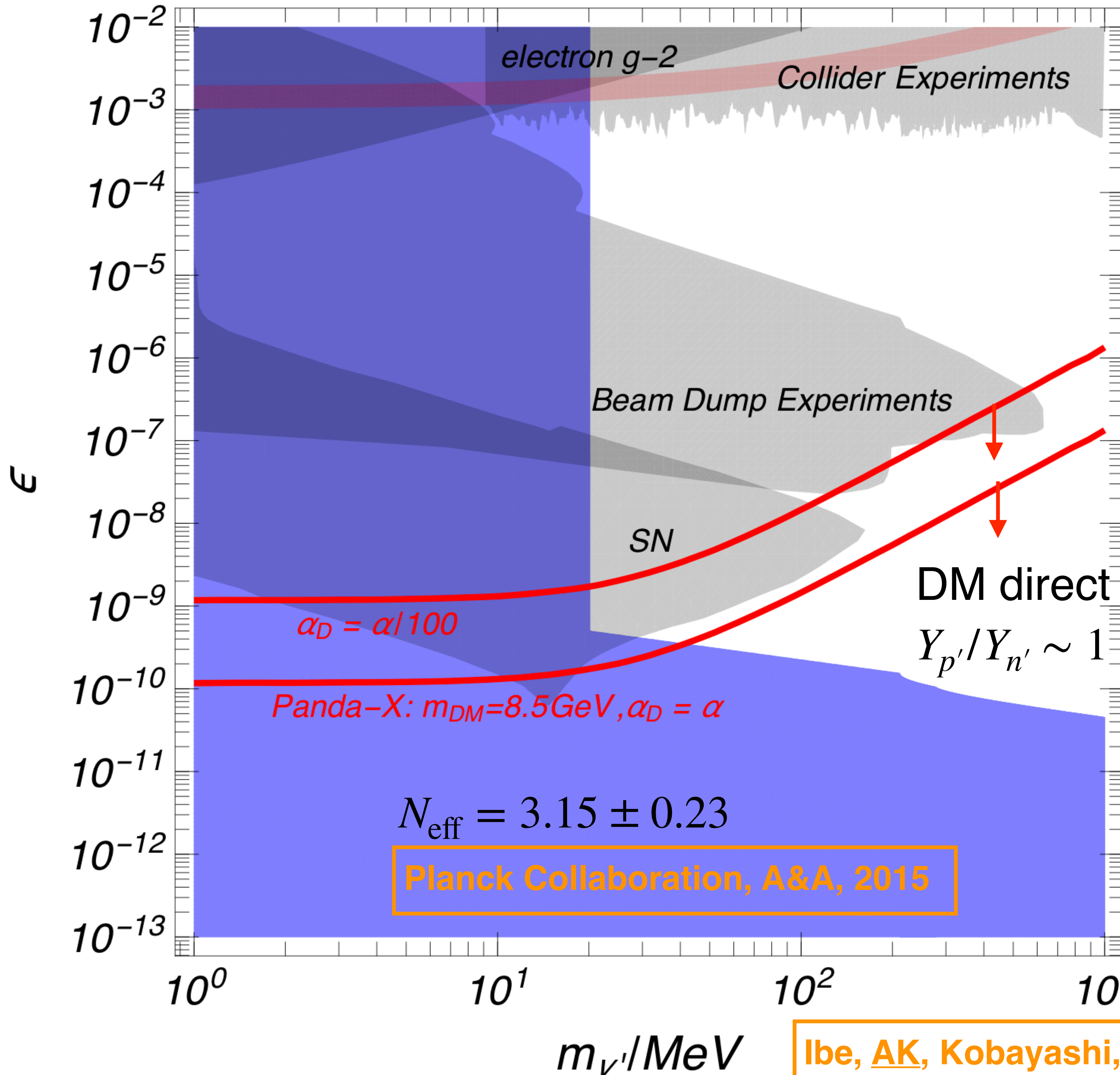
- thermal leptogenesis → $B-L$ asymmetry
- see-saw mechanism → active neutrino mass
- only $\dfrac{y_N}{M_{H_C}^2 M_R}\overline{u}'\overline{d}'\overline{d}'LH$ and ❌ $\dfrac{y_N}{M_{H_C}^2 M_R}\overline{u}\overline{d}\overline{d}LH$

Kinetic mixing between SM and dark photons $\dfrac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$
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

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

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

- portal operator

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

Higher dimensional operator

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

Σ: adjoint scalar

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

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

Mirror grand unification

Ibe, AK, Kobayashi, Kuwahara and Nakano, work in progress

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

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

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

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

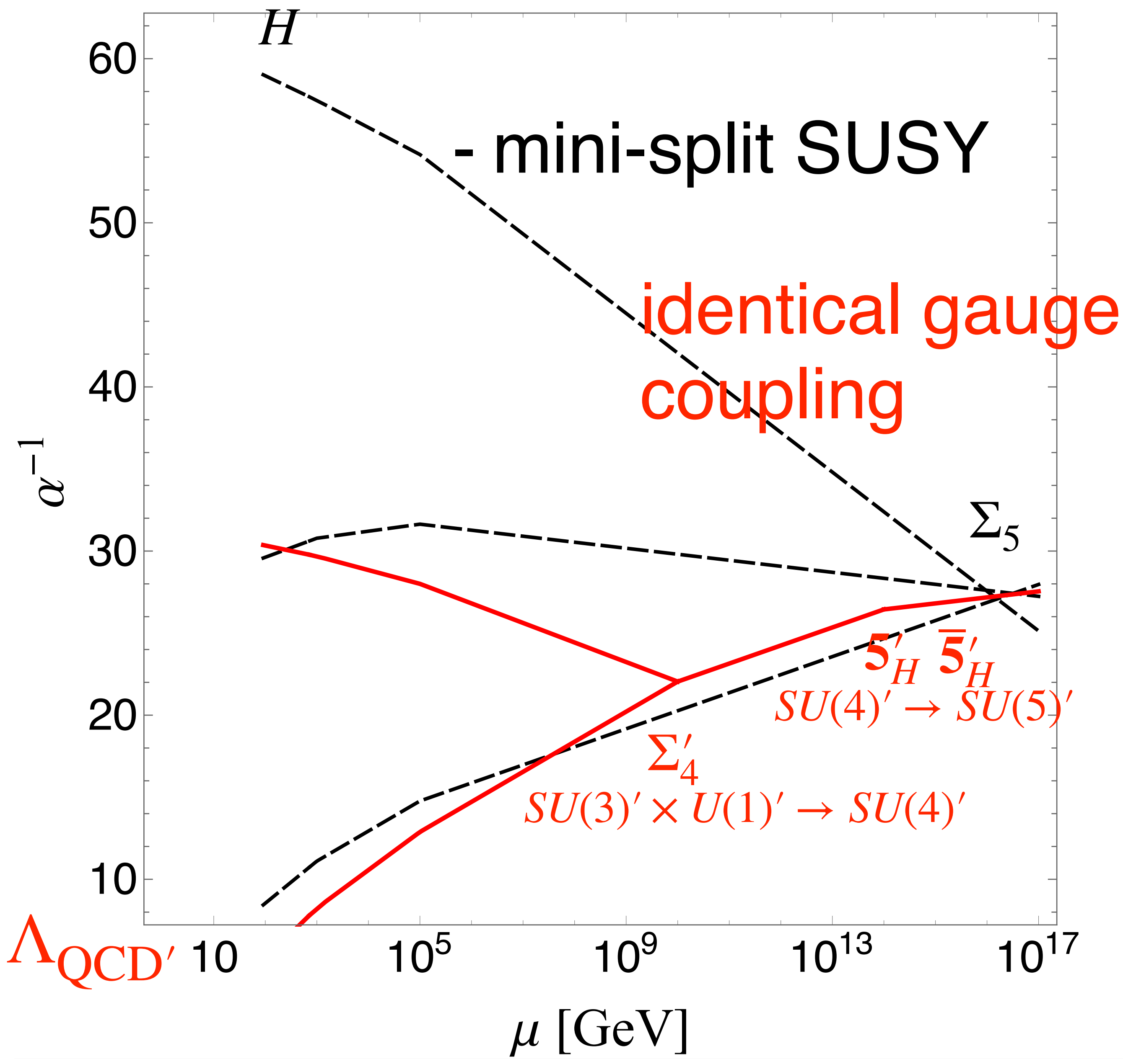
$\overline{\mathbf{5}}' : (\overline{\mathbf{4}}'(\overline{d}', e'), -\nu')$

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

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

large VEV
→ vector-like theory

- softly broken
- mini-split SUSY

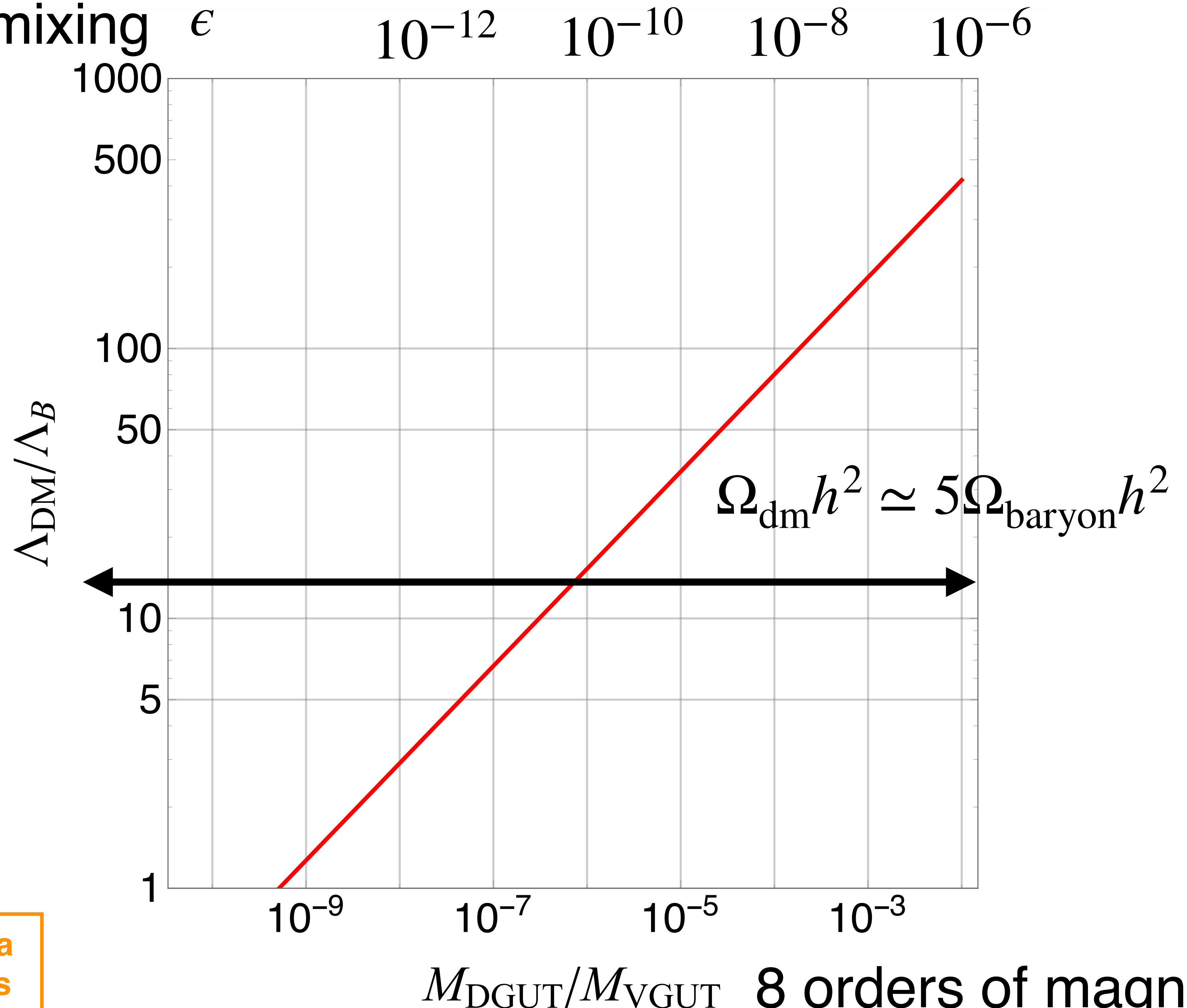


$\Lambda_{QCD} \sim \Lambda_{QCD'}$

Alleviating coincidence

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

kinetic mixing ϵ



just 3 orders of magnitude

8 orders of magnitude

Ibe, AK, Kobayashi, Kuwahara and Nakano, work in progress

Summary

WIMP miracle may have been gone…

- another WIMP miracle related with GUT?
- mini-split SUSY: origin of electroweak symmetry breaking and precise gauge couplings

Small-scale puzzles: diversity of inner rotation curves

- SIDM can explain diversity by changing its distribution according to formed baryon structure (disks)

Velocity-dependent self-scattering cross section is indicated by small-scale puzzles

Asymmetric composite DM is a plausible framework

- DM stability: dark baryon number
- DM relic abundance: co-genesis

Summary

Simple QCD$\times$QED-like dark sector as a working example

- right-handed neutrino: see-saw mechanisms, thermal leptogenesis, and generating portal operator

- dark photon decay: releasing dark sector entropy

- kinetic mixing: DM direct detection

$SU(5) \times SU(4)'$ grand unification

- mini-split SUSY: precise $SU(5)$ grand unification and origins of electroweak and $U(1)'$ breaking

- DM decay into neutrino and dark pion (→ SM electrons)

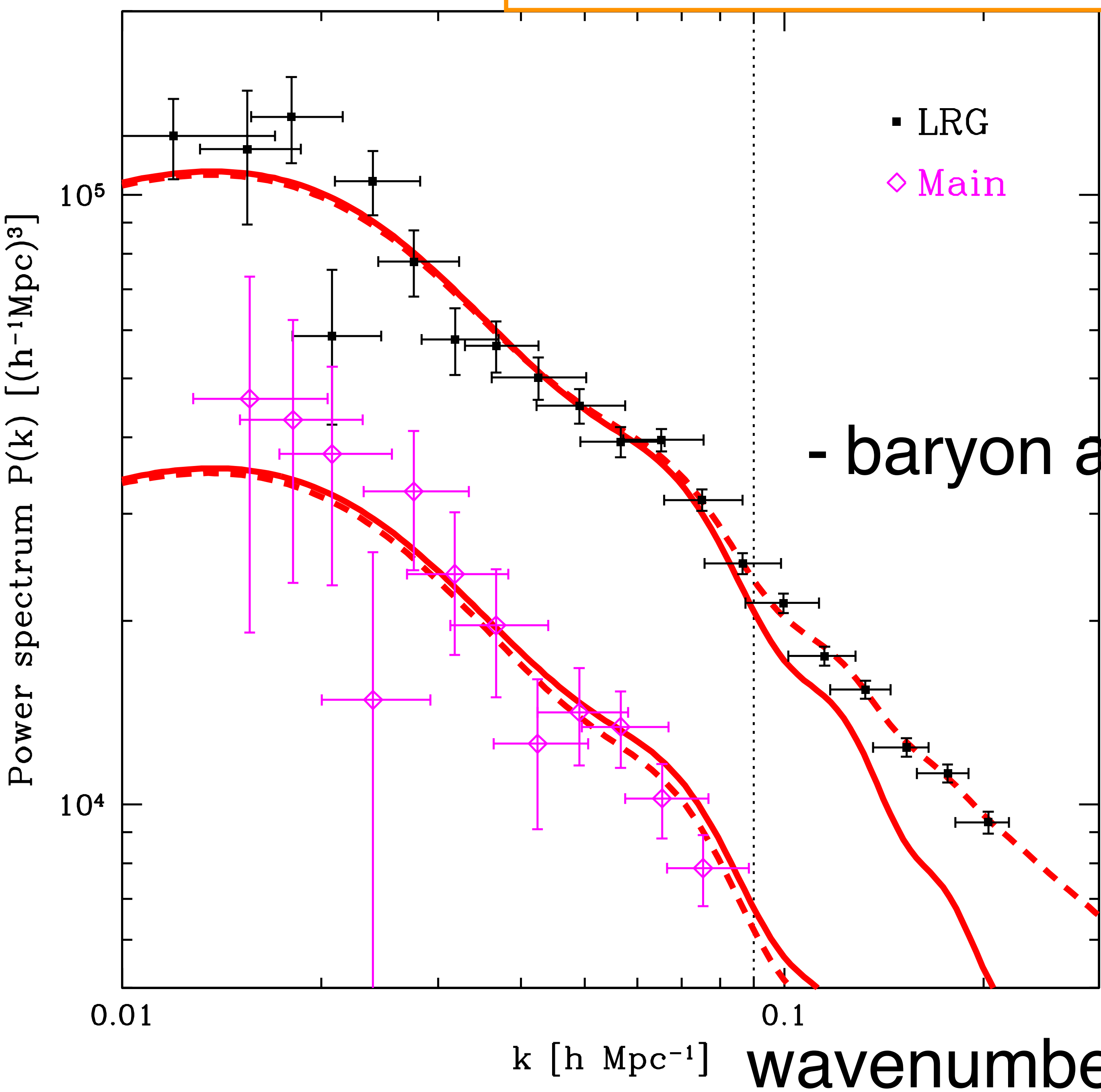
$\rightarrow SU(5) \times SU(5)'/\mathbb{Z}_2$ grand unification?

Part X: Baryon acoustic oscillation

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

SDSS collaboration, PRD, 2006

matter power spectrum



- baryon acoustic oscillation

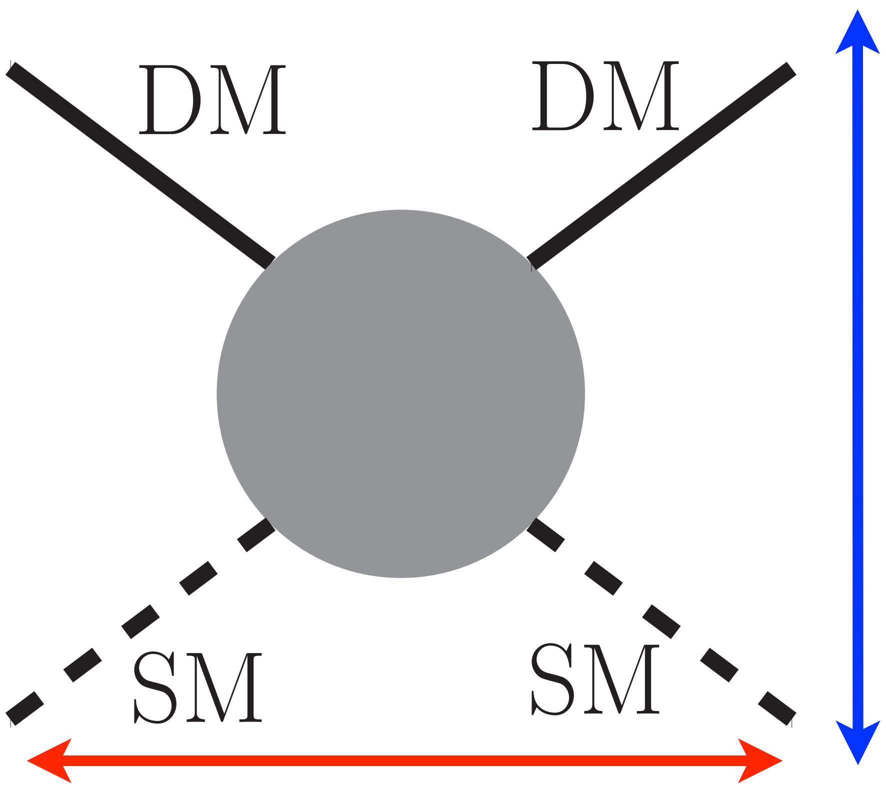
wiggles on the horizon scale at decoupling are imprinted on the matter power spectrum

observed in galaxy clustering

wavenumber [h/Mpc]

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

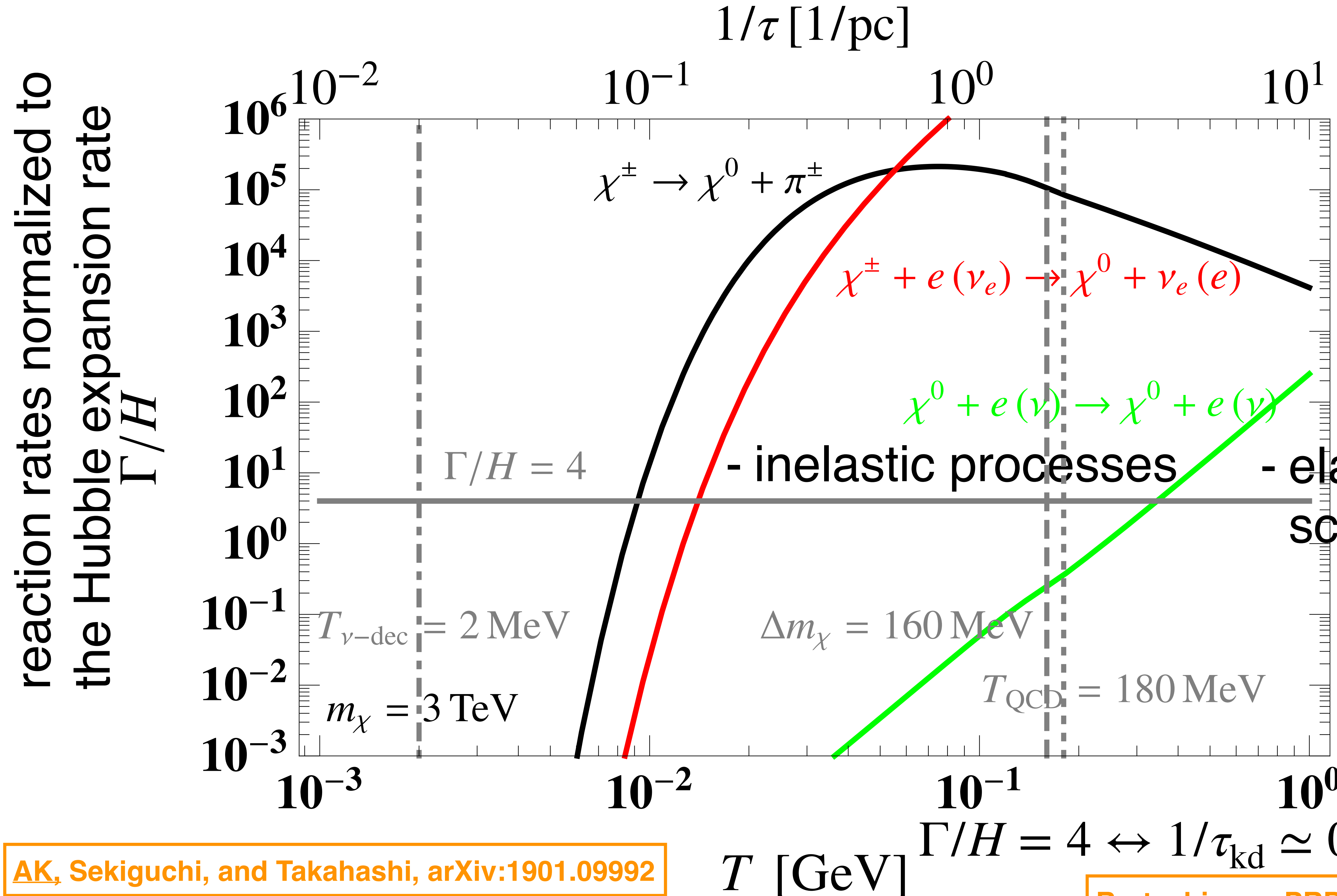
Profumo, Sigurdson, and Kamionkowski, PRL, 2006

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

horizon scale at decoupling ↔ smallest (proto) halos

Shin'ichiro's talk → → may impact indirect detection signals

Kinetic decoupling



- inelastic processes

- elastic scattering

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

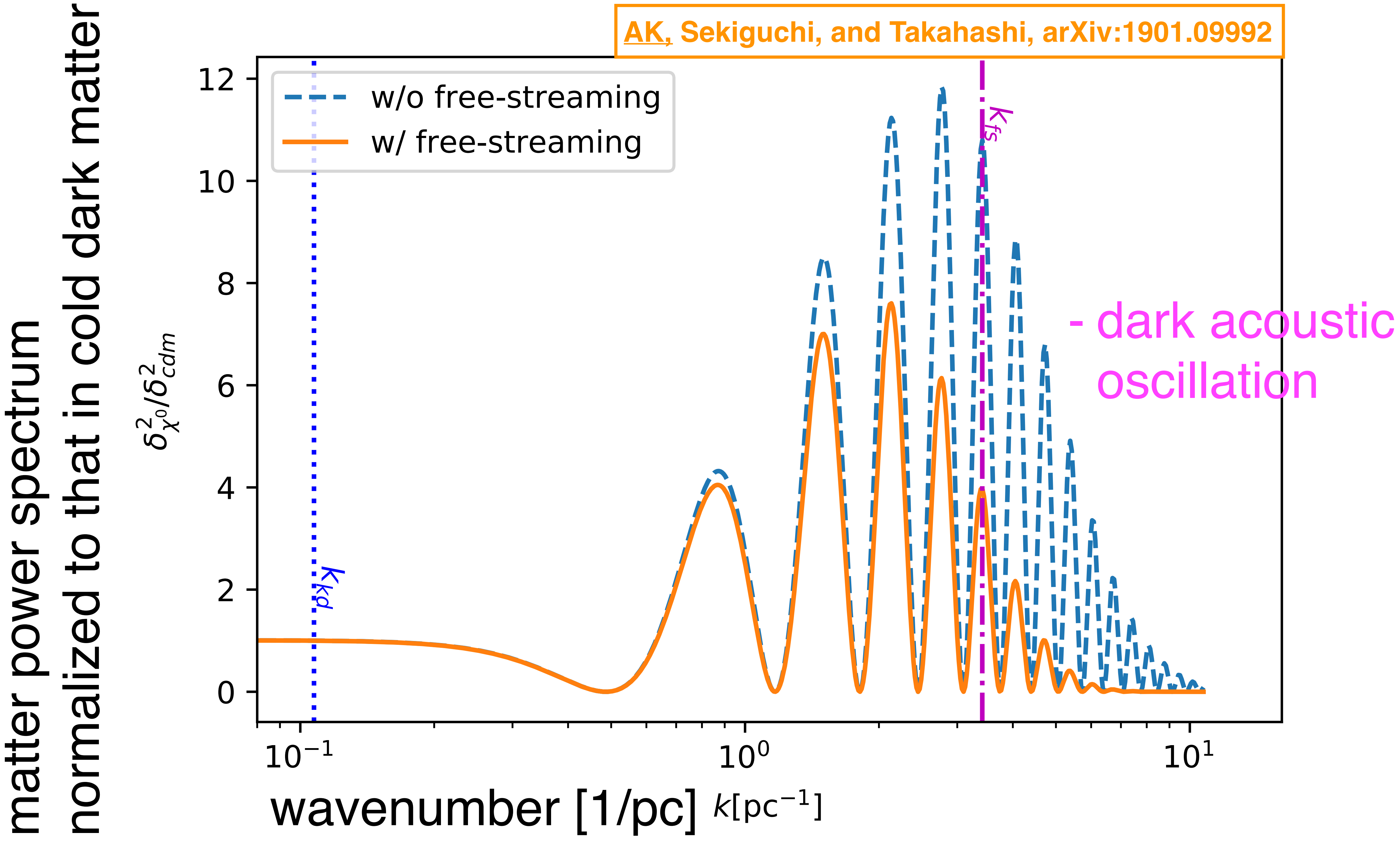
AK, Sekiguchi, and Takahashi, arXiv:1901.09992

Bertschinger, PRD, 2006

Inelastic processes with charginos involve neutralinos in dark acoustic oscillation

Power spectrum

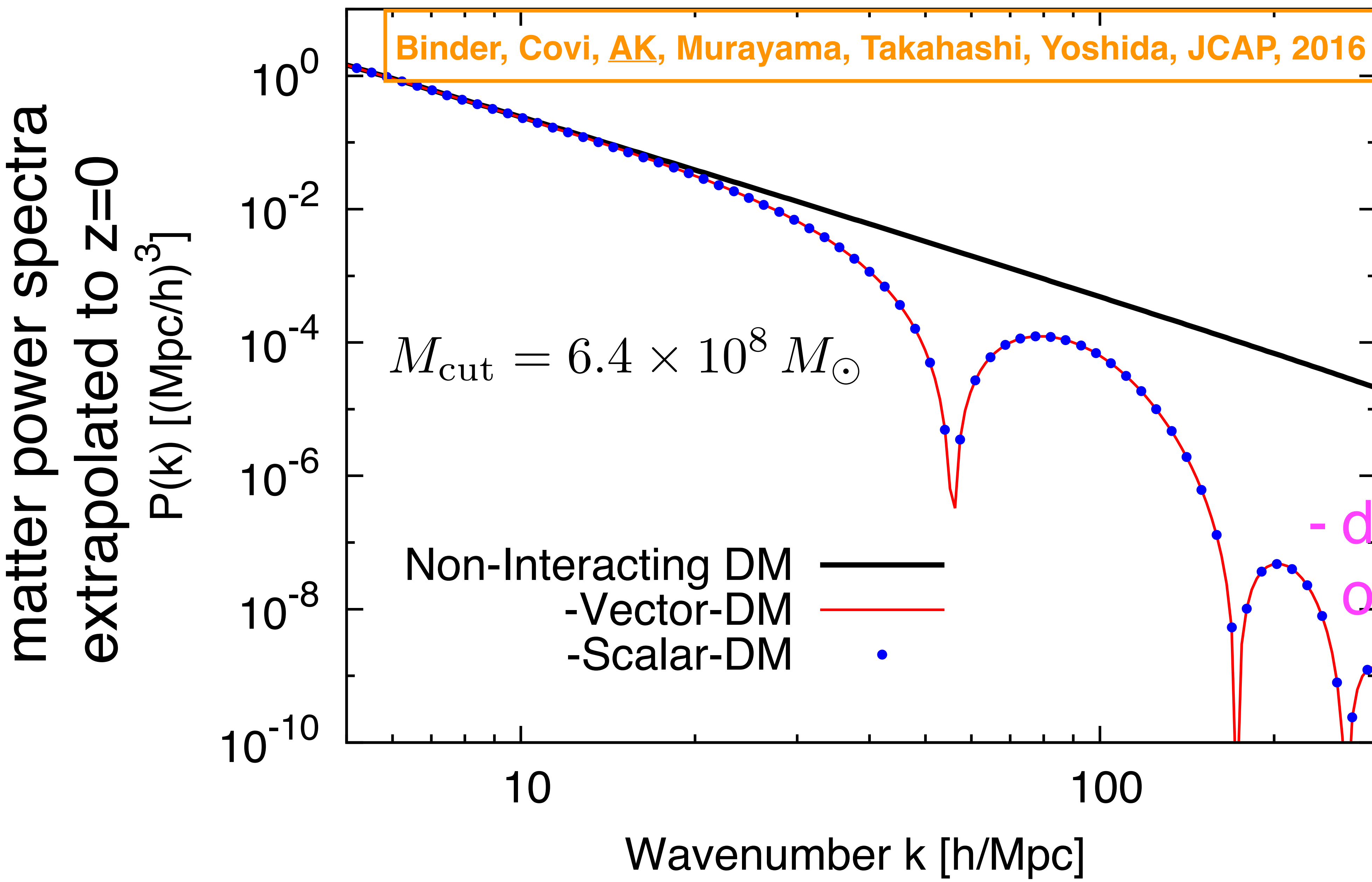
Wino dark matter - inelastic scattering



Peak amplitudes are enhanced!: overshooting phenomenon

Power spectrum

Typical WIMPs - elastic scattering



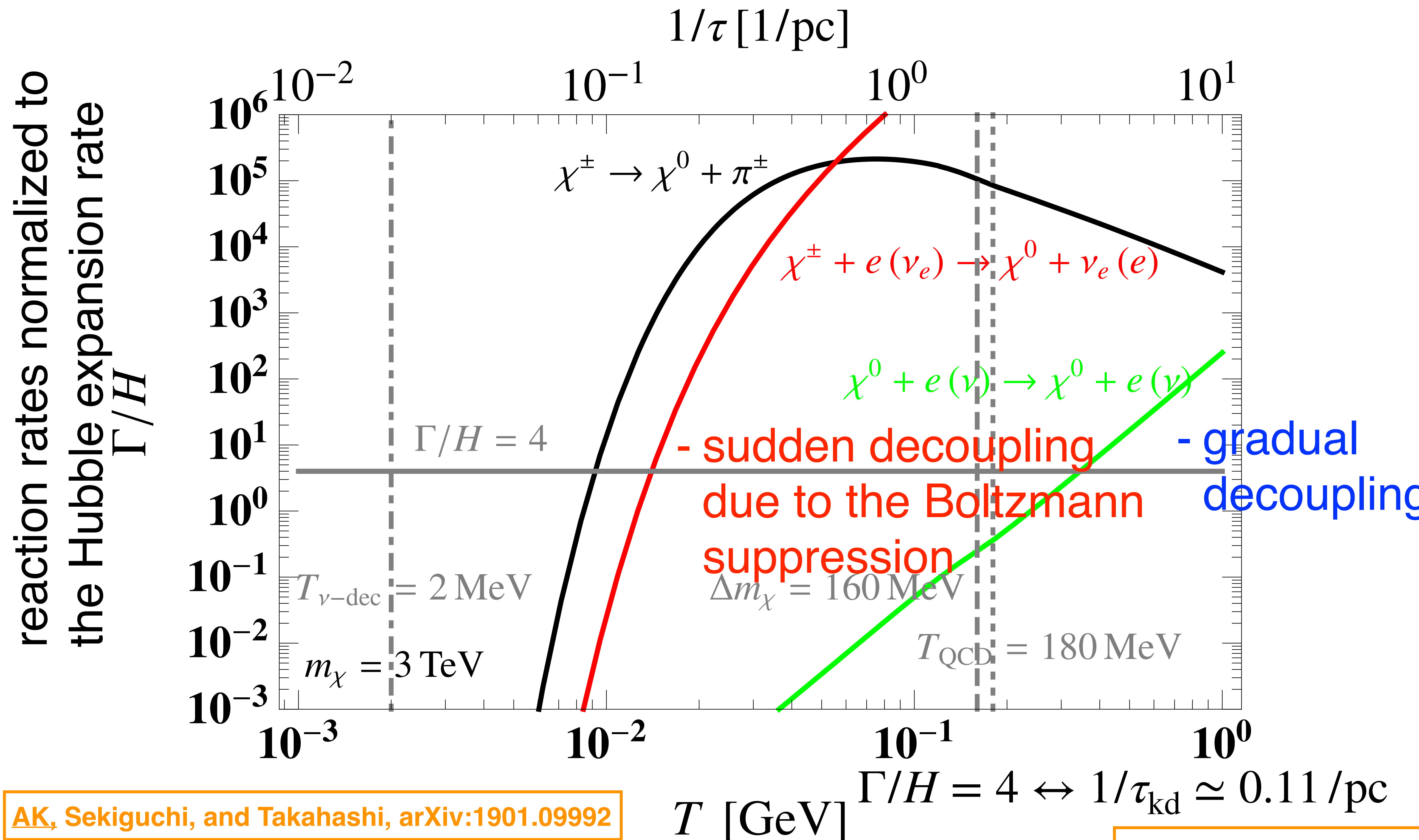
- dark acoustic oscillation

Peak amplitudes are damped

- Landau damping known for baryon acoustic oscilllation

Oscillation phase is averaged over the finite duration of decoupling

Kinetic decoupling



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Bertschinger, PRD, 2006

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

Power spectrum

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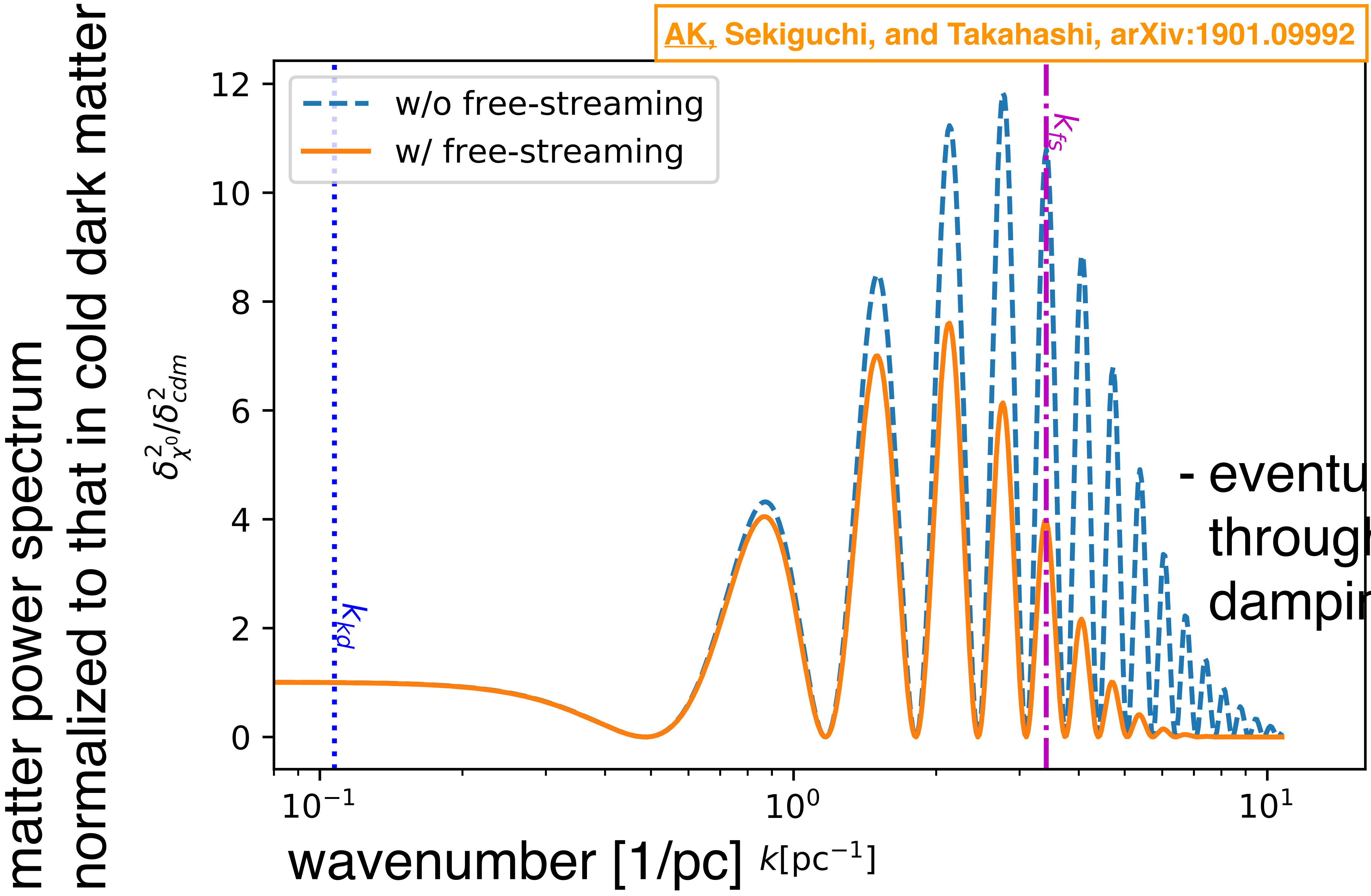
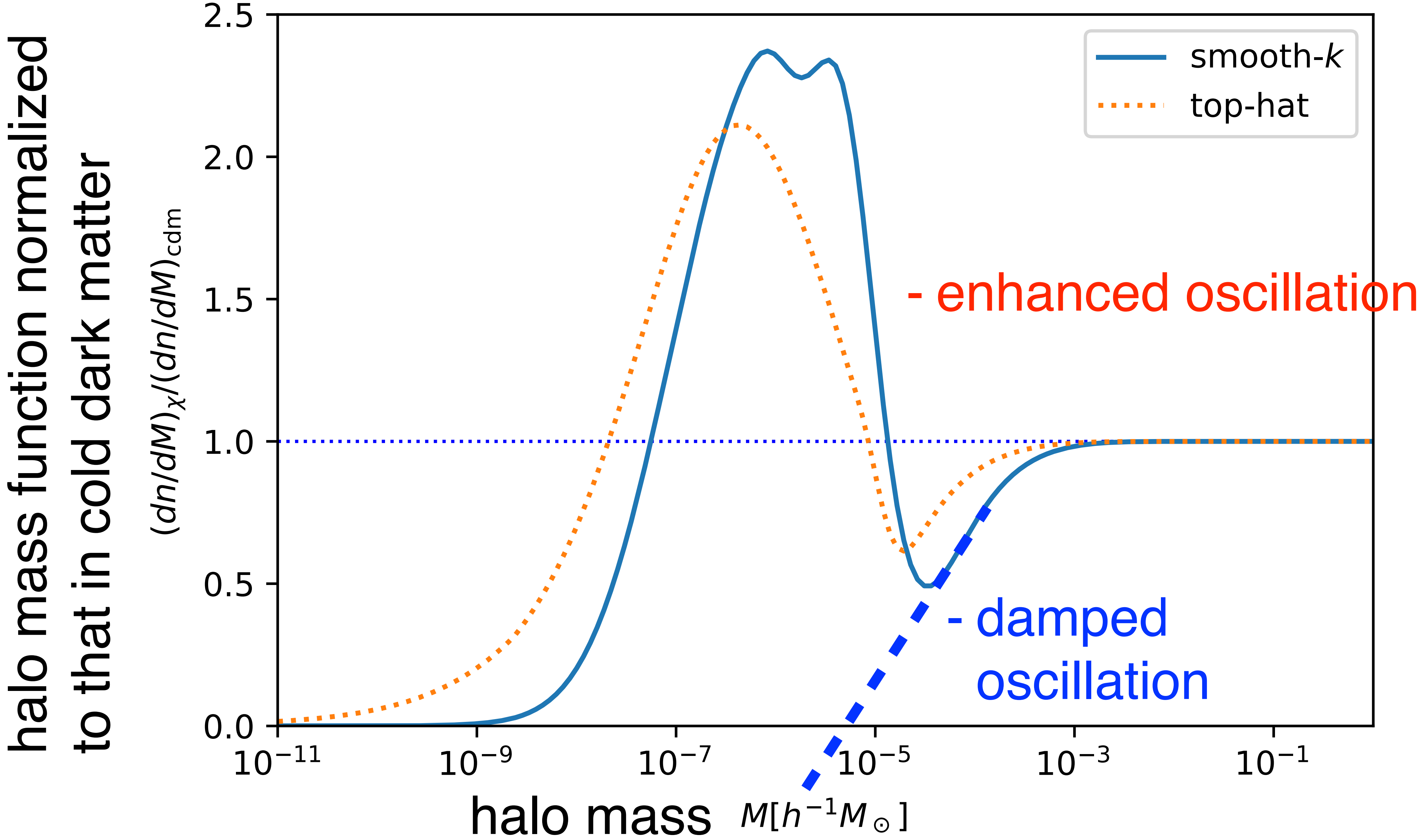


- eventually damped through Landau damping

Free-streaming after decoupling dominates damping

Estimated boost factor



$B(M)$ 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

→ **Shin'ichiro's talk**

Thank you for your attention

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 > 100 TeV; gravitino > 100 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 ~ TeV; higgsino ~ ???: experimental window
  - provide a dark matter candidate
  - precise grand unification of gauge couplings

- another WIMP miracle?

Dark matter candidate

gravitino ~ 100 TeV, gauginos ~ 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 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

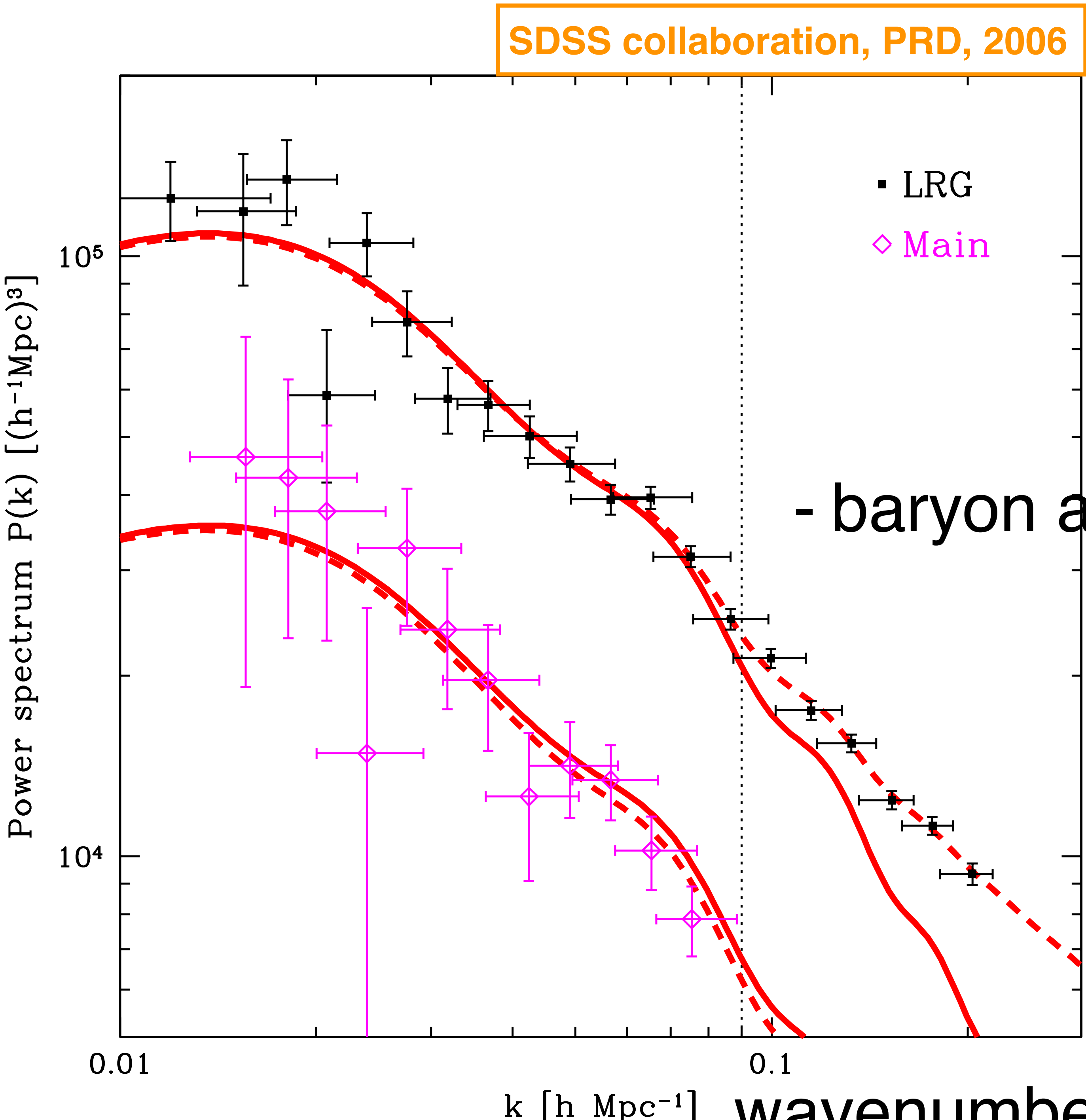
→ $\Omega_\chi h^2 = \Omega_{\rm dm} h^2$ for $m_\chi \simeq 3\,\mathrm{TeV}$

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

- no free parameter left
- accompanied by slightly heavier charged component (EWIMP or electroweakino)

Part 1: Baryon acoustic oscillation

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



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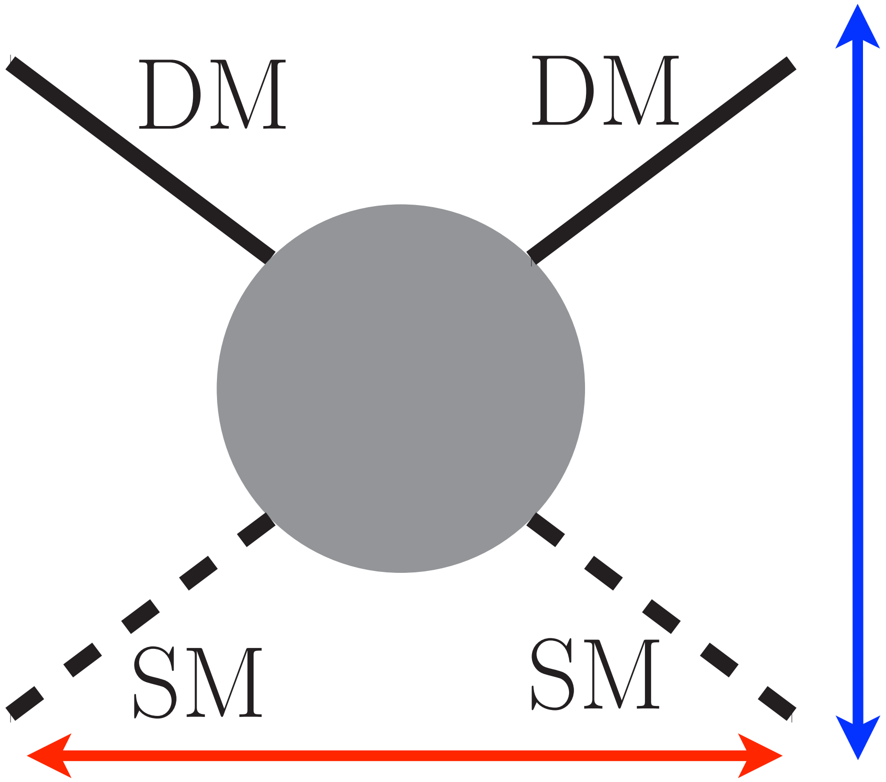

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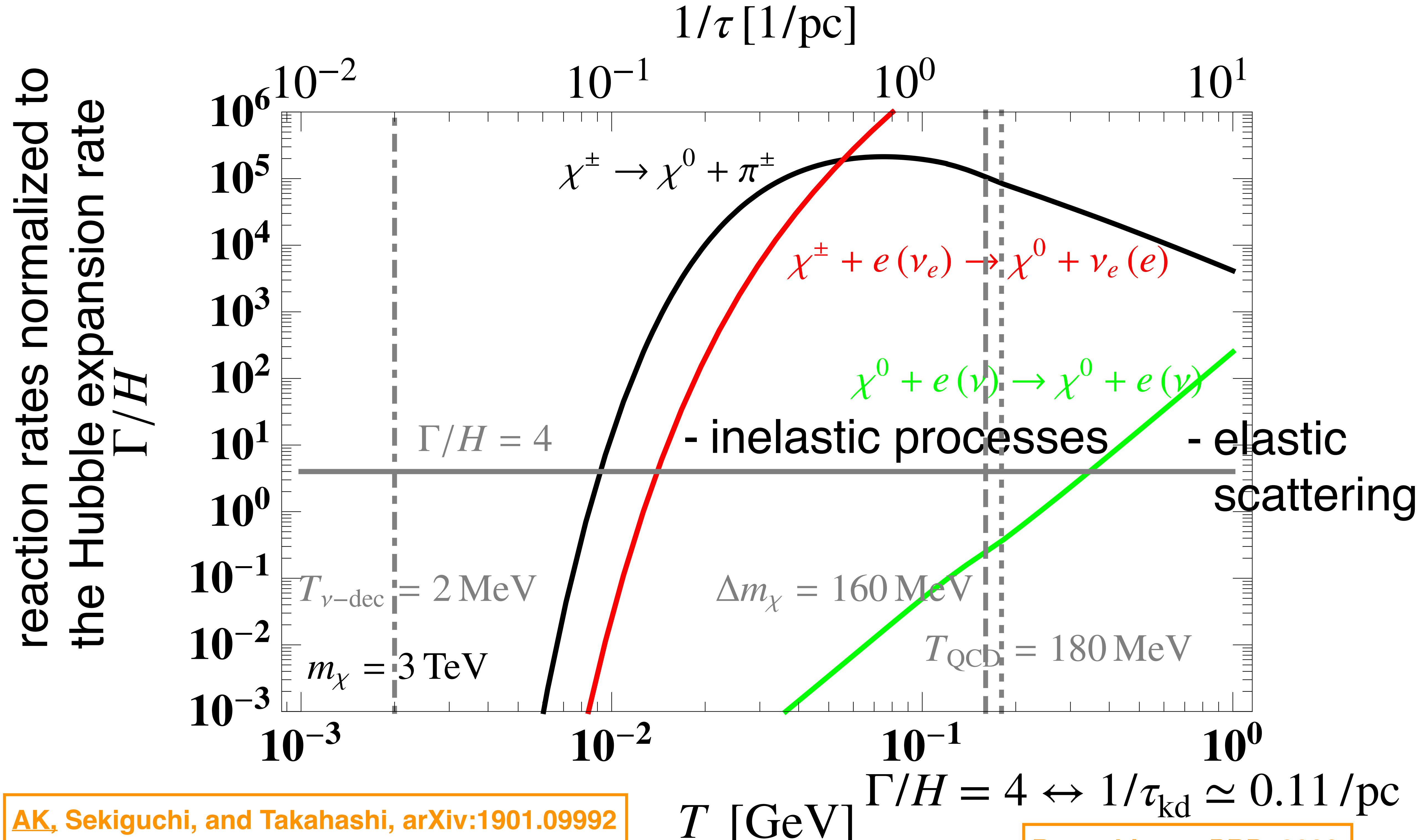
→ may impact indirect detection signals

Kinetic decoupling



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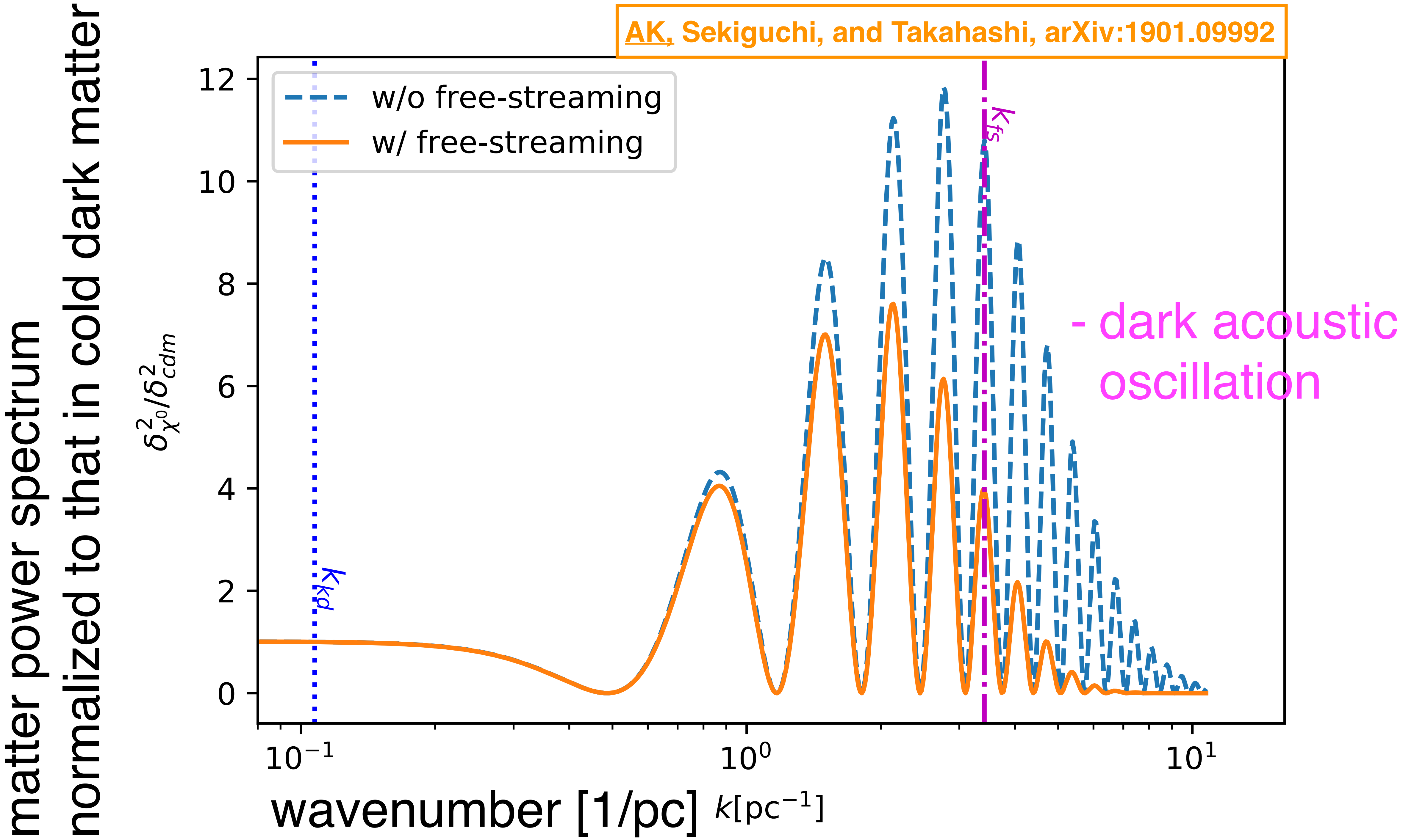

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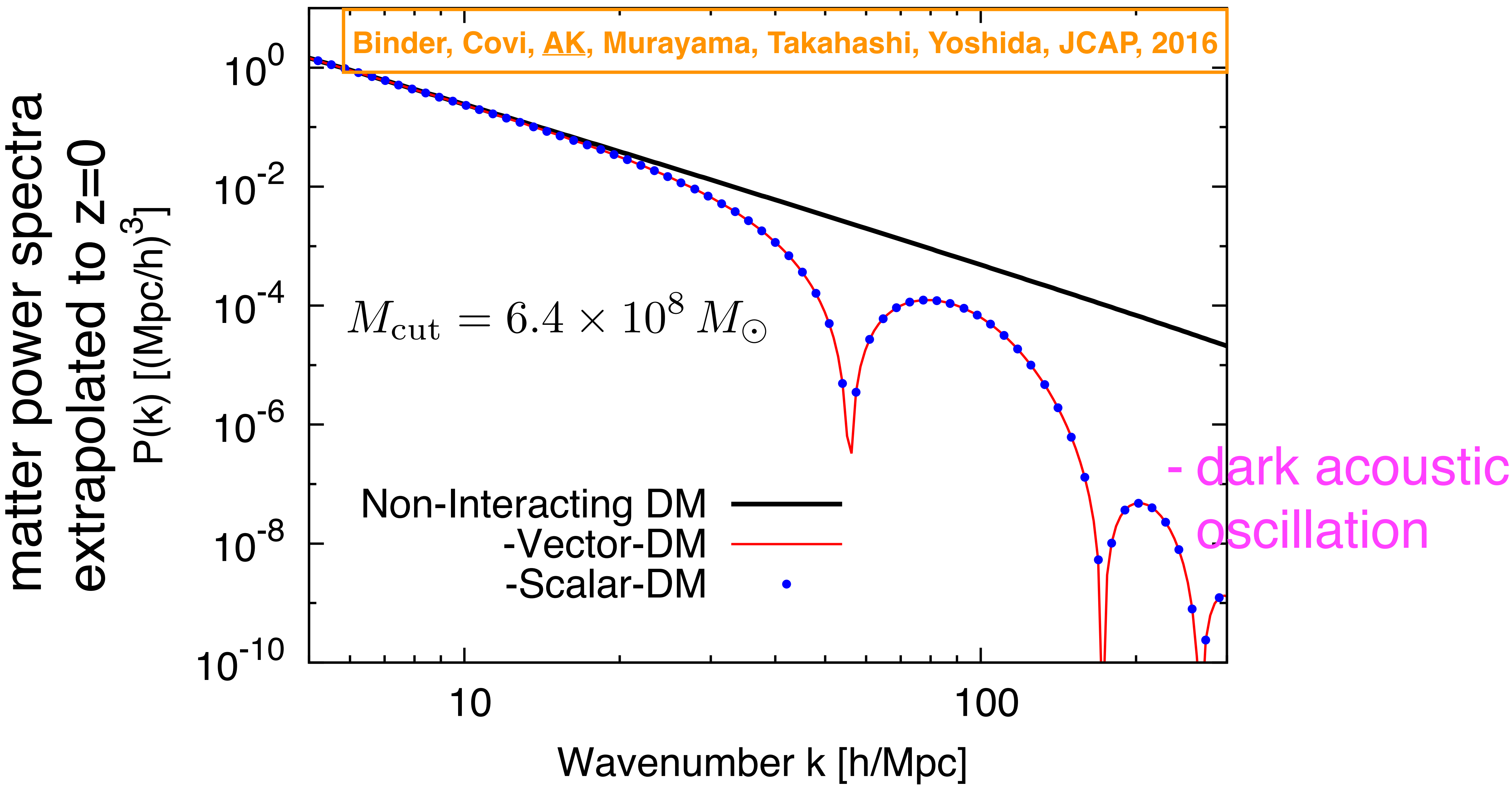

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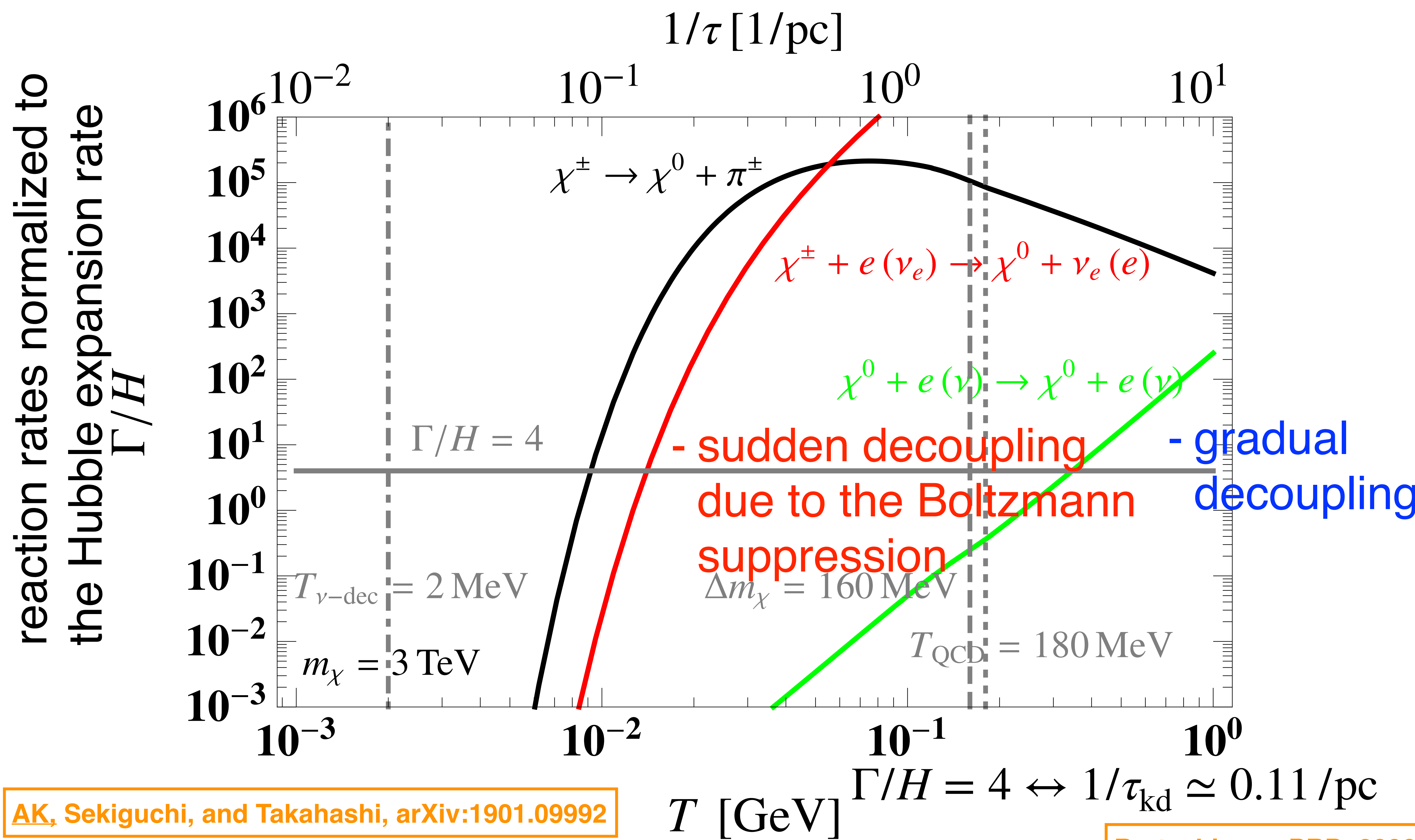

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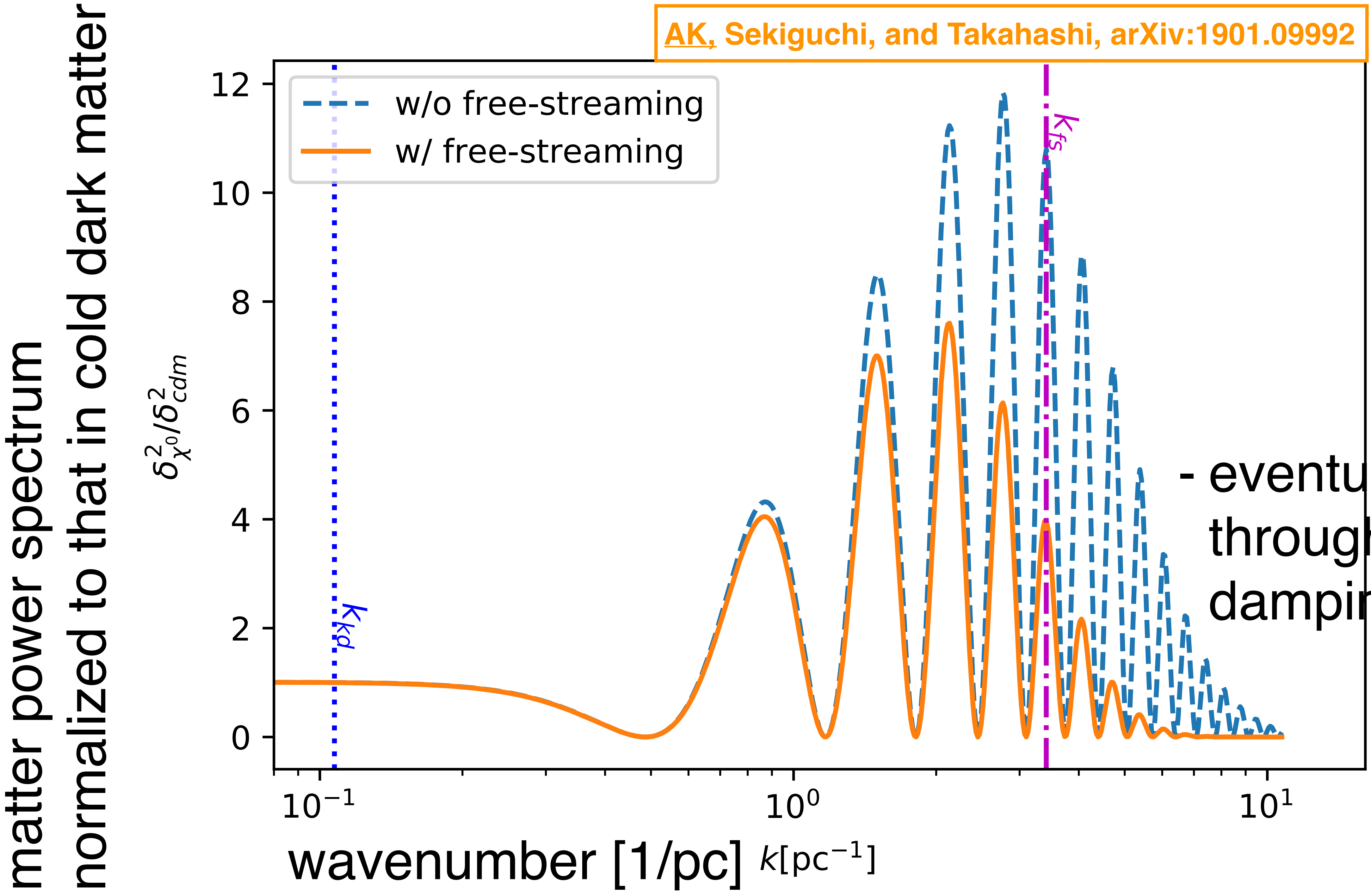


- eventually damped through Landau damping

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 $\bar{L}$

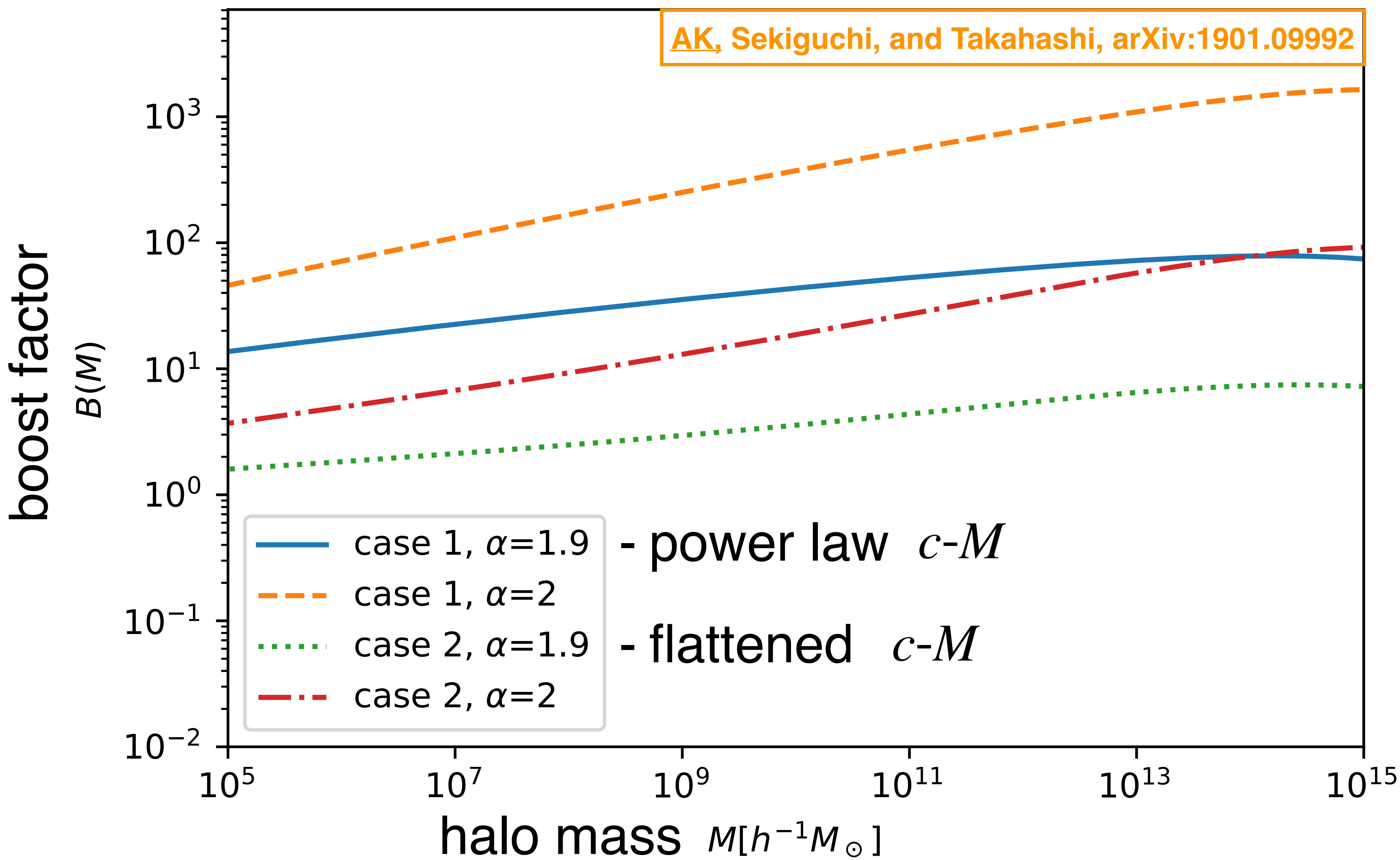
- Navarro-Frenk-White (NFW) profile c-M relation

power-law or flattened?

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

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

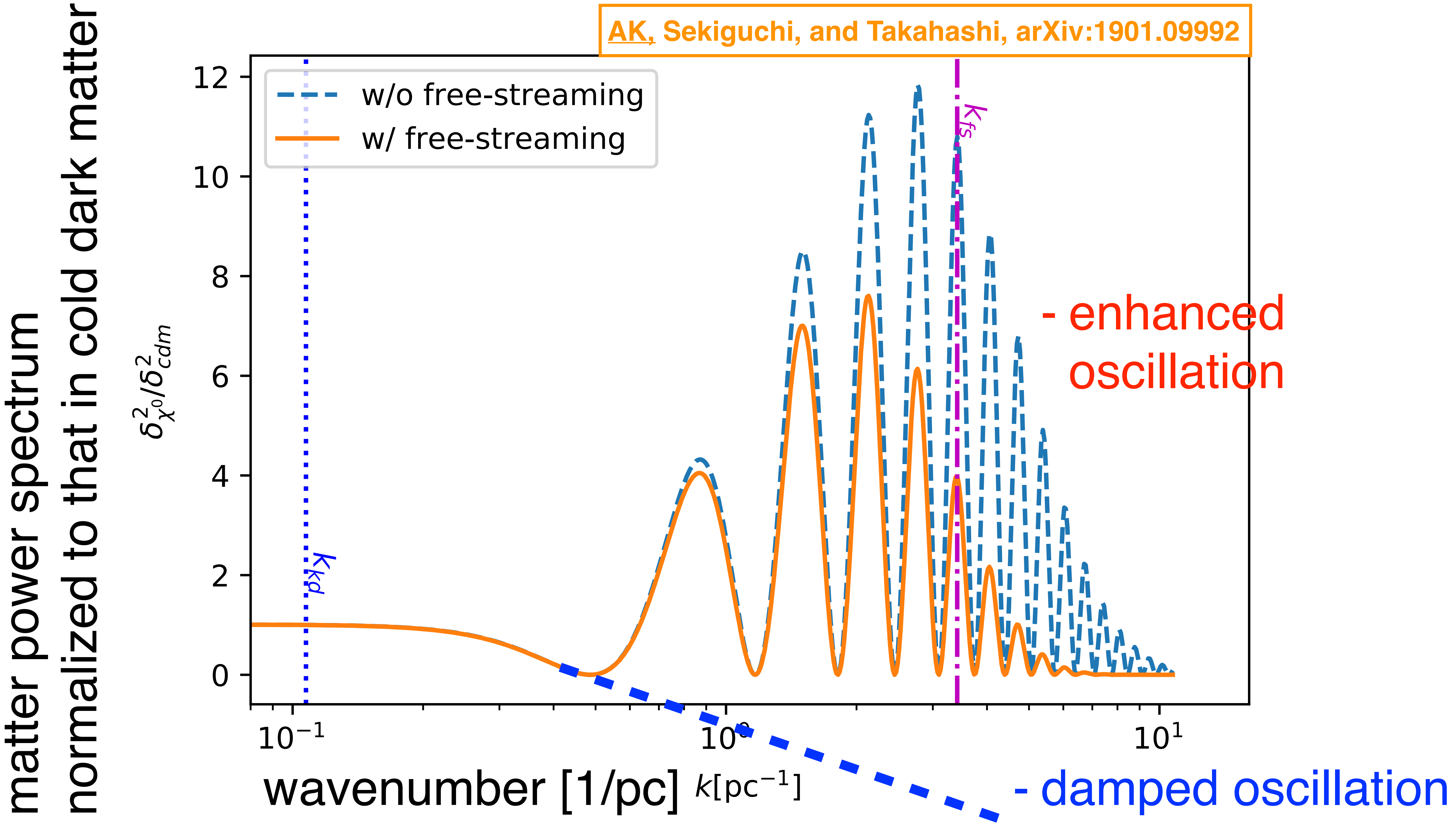
Estimated boost factor



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

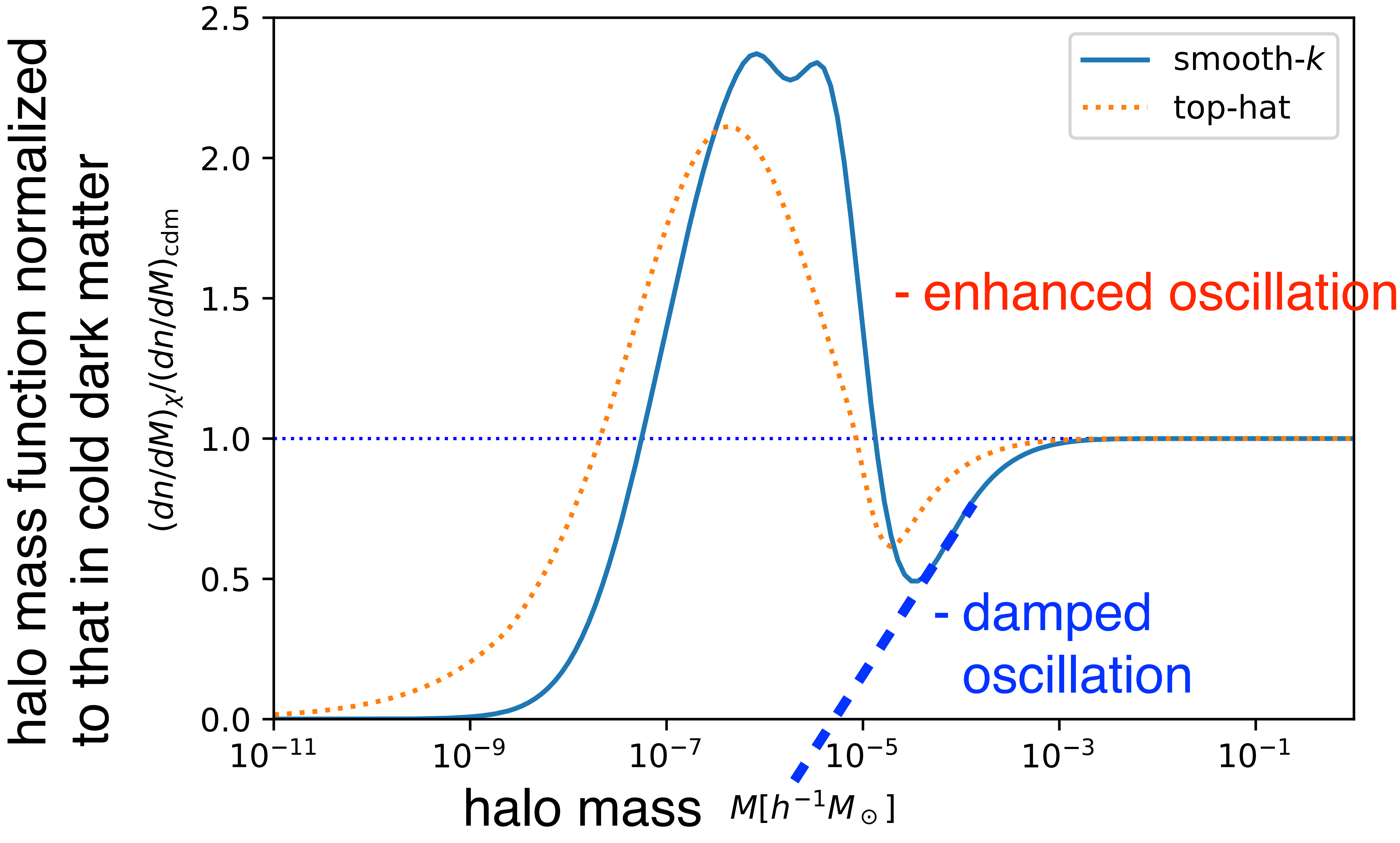
Power spectrum

Wino dark matter - inelastic scattering



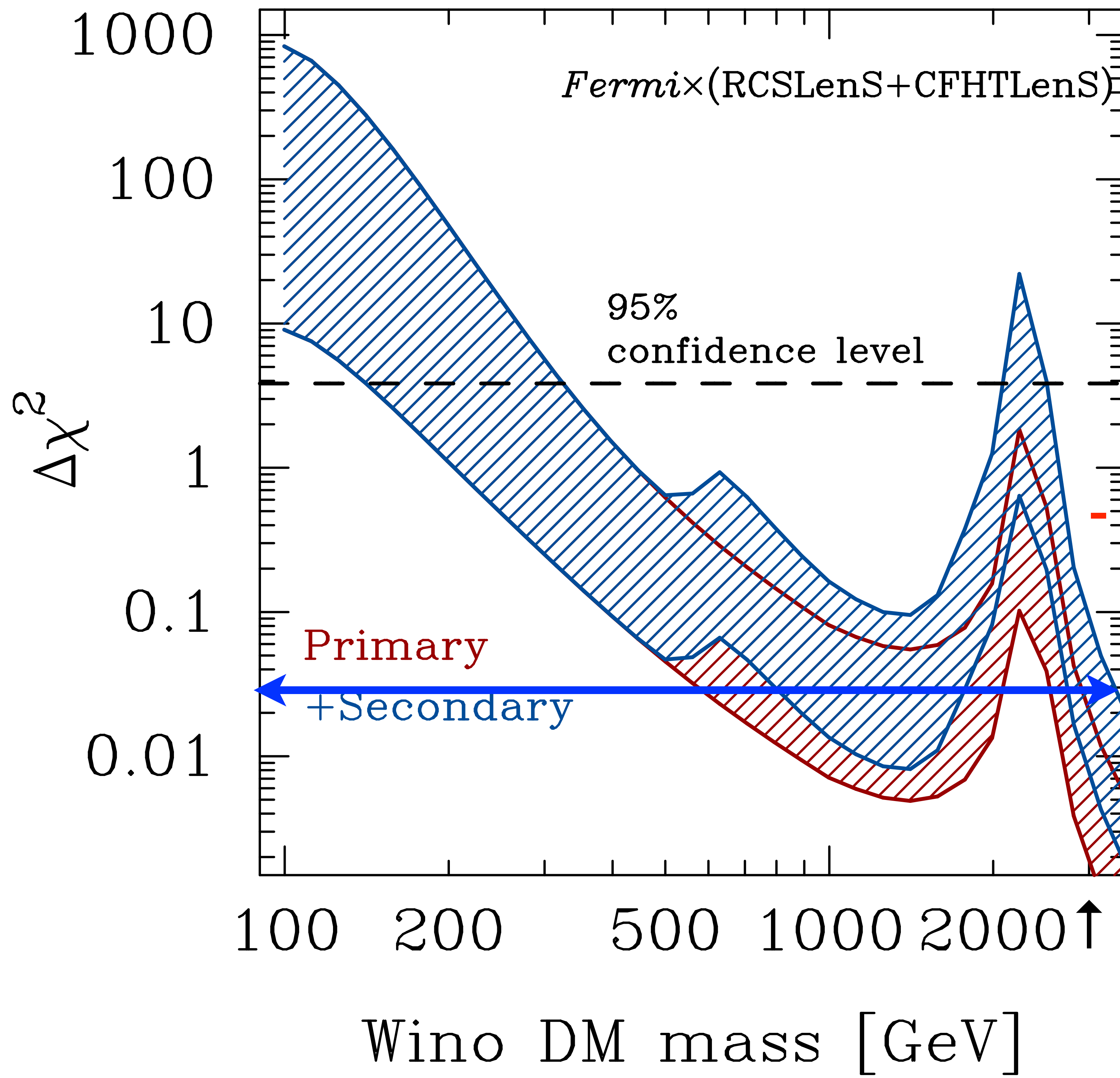
Does the enhanced oscillation impact the boost factor?

Estimated boost factor



$B(M)$ 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!

Minimal halo mass

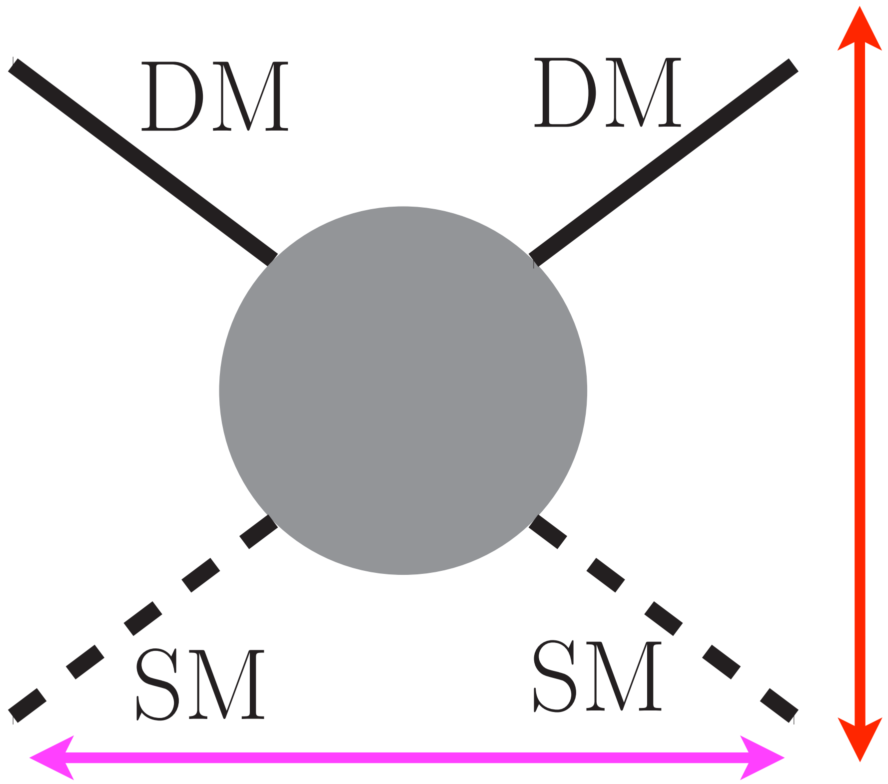
What determines the minimal halo mass?

- primordial density perturbation: $P(k) \propto k^{n_s}$?
- dark matter properties
  - free-streaming: smoothes the primordial density contrast
  - decoupling from primordial plasma: until then dark matter is involved in plasma acoustic oscillation

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

Profumo, Sigurdson, and Kamionkowski, PRL, 2006

...



Crossing symmetry:
elastic process usually lasts even after freeze-out (decoupling of inelastic process)

Dark matter candidate

gravitino ~ 100 TeV, gauginos ~ 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 TeV

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

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

→ good target of indirect detection experiments

Indirect detection experiments

High-energy cosmic rays: anti-particles; gamma-ray

- target approach: galactic center; dwarf galaxies

Cohen, Lisanti, Pierce, and Slatyer, JCAP, 2013

Fan and Reece, JHEP, 2013

Bhattacherjee, Ibe, Ichikawa, Matsumoto, and K. Nishiyama, JHEP, 2014

…

- statistical approach: diffuse background
    - cross-correlations w/ large-scale structure data will enjoy statistical improvement in near future

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

…

Uncertainty: dark matte distribution - J factor

- density profile of a dark matter halo $\langle\rho\rangle_{\rm coarse\ graining}$
- flux multiplier/boost factor: $\langle\rho^2\rangle/\langle\rho\rangle^2 \geq 1$
    - (sub) halo mass function up to the smallest halos
    - $\langle\rho\rangle$ up to the smallest halos: c-M relation

Elastic processes

Fokker-Planck approximation:
expanding the collision term w.r.t. $q/p \ll 1$

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

differential cross section

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

thermal momentum squared $\propto p^2$ **momentum transfer squared** $\propto q^2$

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

T : temperature
$u^\mu(x)$: bulk velocity
of thermal bath plasma

Elastic processes for neutral wino

Elastic scattering is subdominant!

- $\chi^0 W^\pm \to \chi^0 W^\pm$: related with perturbative annihilation

  inefficient after $T \sim m_W$

- $\chi^0 L \to \chi^0 L \quad (L = \nu,\, e)$: loop suppressed **Ibe, AK, and Matsumoto, PRD, 2013**

$$\gamma_{\rm ela} = 8\frac{100}{\pi^3} g_{\rm loop}^2 G_F^4 m_W^4 \frac{T^6}{m_\chi}$$

$$g_{\rm loop} = \frac{1}{3\pi^2}\left(2(8-\omega-\omega^2)\sqrt{\frac{\omega}{4-\omega}}\arctan\left(\sqrt{\frac{4-\omega}{\omega}}\right) - \omega\left(2-(3+\omega)\ln\omega\right)\right)$$

$$\omega = m_W^2/m_\chi^2$$

inefficient after $T \sim 1\,{\rm GeV}$

Relevant processes for charged wino

$\chi^{\pm}$ is in kinetic equilibrium with primordial plasma $\gamma,\ e,\ \nu,\ \pi, \ldots$

$$f_{\chi^{\pm}}(\mathbf{p}) \approx \frac{n_{\chi^{\pm}}}{g_{\chi^{\pm}}}\left(\frac{2\pi}{m_\chi T}\right)^{3/2} \exp\left(-\frac{(\mathbf{p}-m_\chi \mathbf{u})^2}{2m_\chi T}\right)$$

$\mathbf{u}$: bulk velocity

$\chi^{\pm}$ and χ^0 are in chemical equilibrium through inelastic processes

Arcadi and Ullio, PRD, 2011

- $\chi^{\pm} \to \chi^0 + \pi^{\pm}$: decay

$$\Gamma_{\rm dec} \approx \frac{f_\pi^2 G_F^2 |V_{ud}|^2}{\pi} \Delta m_\chi^3 \sqrt{1-\frac{m_{\pi^{\pm}}^2}{\Delta m_\chi^2}}$$

- $\chi^{\pm}L' \to \chi^0 L$: inelastic scattering

$$\Gamma_{\rm inela} = 2\frac{8G_F^2}{\pi^3}T^3\left(\Delta m_\chi^2 + 6\Delta m_\chi T + 12T^2\right)$$

$$n_{\chi^{\pm}} \approx \frac{g_{\chi^{\pm}}}{g_{\chi^0}} n_{\chi^0} \exp\left(-\frac{\Delta m_\chi}{T}\right)$$

Relevant processes for neutral wino

Inelastic processes keep χ^0 in kinetic equilibrium and are dominant

- $\chi^0 + \pi^\pm \to \chi^\pm, \quad \chi^0 L \to \chi^\pm L'$: conversion approximation

Arcadi and Ullio, PRD, 2011

$\Delta m_\chi, T << \sqrt{m_\chi T}$

$$\frac{1}{E} C_{\chi^0,\mathrm{inela}} \approx g_{\chi^\pm}(\Gamma_{\mathrm{dec}} + \Gamma_{\mathrm{inela}}) \left(f_{\chi^\pm} - f_{\chi^0} \exp\left(-\frac{\Delta m_\chi}{T} \right) \right)$$

For χ^0, interaction rates are suppressed by $\exp\left(-\Delta m_\chi / T\right)$

- efficient until $T \sim \Delta m_\chi / 20$

Cosmological background

- synchronous gauge

$$ds^2 = a^2\left(-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j\right)\,, \quad h_{ij} = \hat{k}_i\hat{k}_j h + \left(\hat{k}_i\hat{k}_j - \frac{1}{3}\delta_{ij}\right)\eta$$

- evolution of number density $\quad n_\chi = g_\chi \int \frac{d^3\mathbf{p}}{(2\pi)^3} f_\chi$

$$\dot{n}_{\chi^0} + 3\frac{\dot{a}}{a}n_{\chi^0} = -\left(\dot{n}_{\chi^\pm} - 3\frac{\dot{a}}{a}n_{\chi^\pm}\right)(\approx 0)\,,$$

- total wino number conservation

- chemical equilibrium

- evolution of temperature $\quad 3m_\chi T_\chi n_\chi = g_\chi \int \frac{d^3\mathbf{p}}{(2\pi)^3}\mathbf{p}^2 f_\chi$

$$\dot{T}_{\chi^0} + 2\frac{\dot{a}}{a}T_{\chi^0} \approx a\left[g_{\chi^\pm}(\Gamma_{\rm dec} + \Gamma_{\rm inela})\exp\left(-\frac{\Delta m_\chi}{T}\right) + 2g_{\chi^0}\gamma_{\rm ela}\right]\left(T - T_{\chi^0}\right)$$

- effective reaction rate

Cosmological perturbations

- evolution of density perturbation $n_\chi \delta_\chi = g_\chi \int \frac{d^3\mathbf{p}}{(2\pi)^3} \delta f_\chi$

$$\dot{\delta}_{\chi^0} + \theta_{\chi^0} + \frac{1}{2}\dot{h} = -\left(\frac{\dot{n}_{\chi^0}}{n_{\chi^0}} + 3\frac{\dot{a}}{a}\right)(\delta_{\chi^0} - \delta_{\chi^\pm}) - \frac{n_{\chi^\pm}}{n_{\chi^0}}\left(\dot{\delta}_{\chi^\pm} + \theta_T + \frac{1}{2}\dot{h}\right)(\approx 0)$$

- total wino number conservation

$$\delta_{\chi^\pm} \approx \delta_{\chi^0} + \frac{\Delta m_\chi}{T}\delta_T\,, \qquad \delta_T = \frac{\delta T}{T}\,, \quad \theta_T = i\mathbf{k}\cdot\mathbf{u}$$

- chemical equilibrium

- evolution of velocity perturbation $m_\chi n_\chi \theta_\chi = g_\chi \int \frac{d^3\mathbf{p}}{(2\pi)^3}(i\mathbf{k}\cdot\mathbf{p})\delta f_\chi$

$$\dot{\theta}_{\chi^0} + \frac{\dot{a}}{a}\theta_{\chi^0} \approx a g_{\chi^\pm}(\Gamma_{\text{dec}} + \Gamma_{\text{inela}})\exp\left(-\frac{\Delta m_\chi}{T}\right)\left(\theta_T - \theta_{\chi^0}\right)$$

- the same effective reaction rate as for temperature evolution

- sour term drives dark acoustic oscillation

Overshooting phenomenon

Seen when kinetic decoupling proceeds rapidly

$$\frac{1}{\Gamma/H}\frac{d(\Gamma/H)}{dt} \gg H \quad \text{around kinetic decoupling} \quad \Gamma/H \sim 1$$

Discovered for Coulomb scattering of charged massive particle (CHAMP) with electrons $\Gamma \propto \exp\left(-m_e/T\right)$ $T_{\rm kd} \sim m_e/20$

AK, Kohri, Takahashi, and Yoshida, PRD, 2017

Analytic approximation can be derived for $\Gamma/H = \left(\tau/\tau_{\rm d}\right)^n$

Extension with fudge factors for $k \gg k_{\rm kd}$

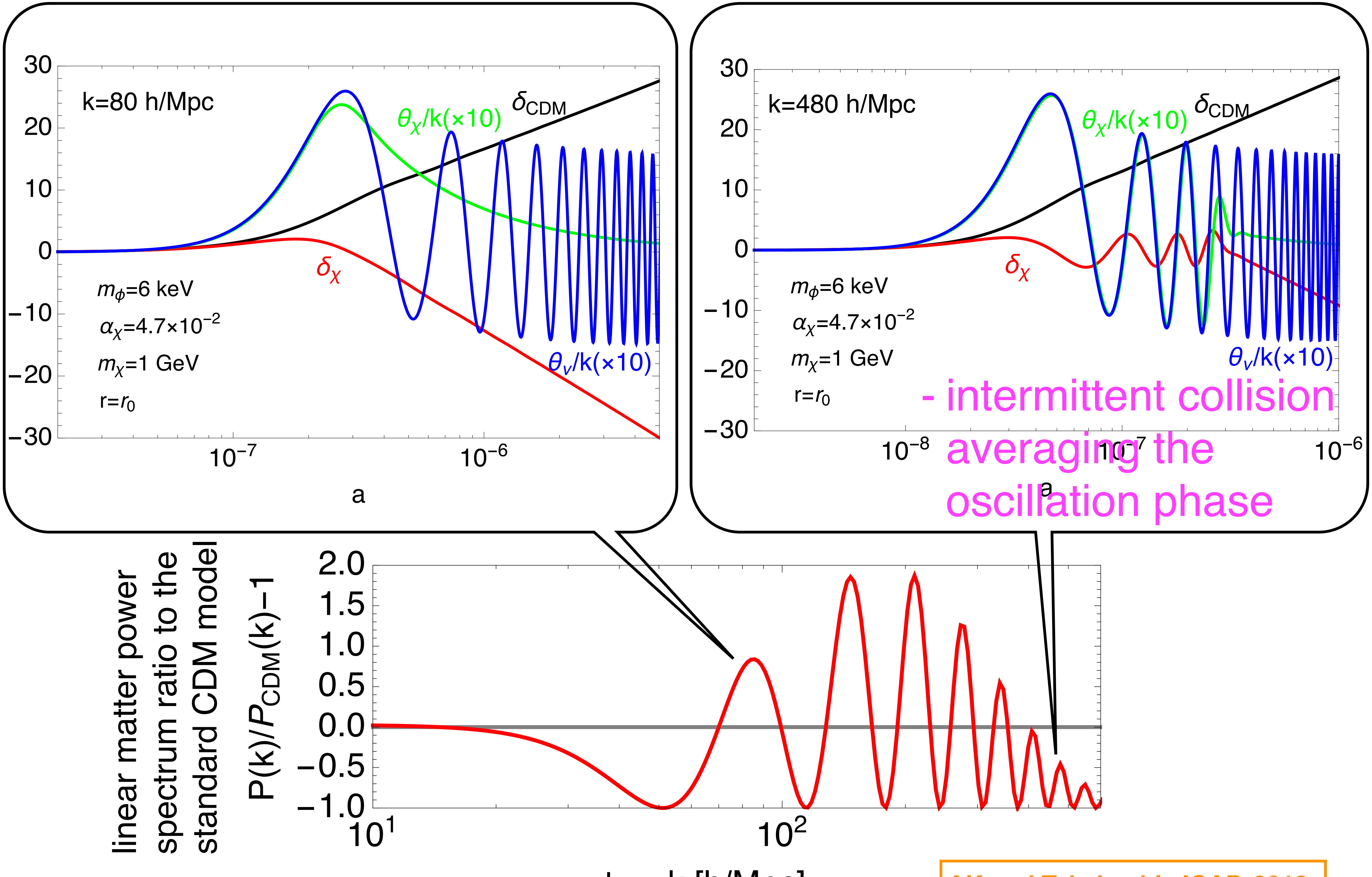
AK and Takahashi, JCAP, 2018

$$\frac{\delta^2_{\chi^0}}{\delta^2_{\rm cdm}} \approx c_{\mathcal{N}}\frac{4\pi}{n}\exp\left(-\frac{k}{k_{\rm damp}}\right)\left(\frac{k}{2\sqrt{3}k_{\rm kd}}\right)^3\sin^2\left(\frac{k}{\sqrt{3}k_{\rm kd}}\right)$$

- damping - enhancement

$$k_{\rm damp} = c_{\rm damp}\frac{n}{\pi}\sqrt{3}k_{\rm kd}\,, \qquad k_{\rm kd} = \frac{c_{\rm kd}}{\tau_{\rm kd}}$$

Evolution of adiabatic perturbation



AK and Takahashi, JCAP, 2018

Free-streaming

Dark matter thermal motion is neglected

- pressure, sound speed, …

Higher multipoles in the Boltzmann hierarchy are truncated

- anisotropic inertia, entropy perturbation, …

Free-streaming is taken into account as $\delta_\chi \to \delta_\chi \times \exp\left(-\frac{k^2}{2k_{\rm fs}(\tau)^2}\right)$

Bertschinger, PRD, 2006

$$k_{\rm fs}^{-1} = \sqrt{\frac{6T_{\rm kd}}{5m_{\chi^0}}}\int_{\tau_*}^{\tau}\frac{d\tau'}{a(\tau')/a_{\rm kd}} \approx \sqrt{\frac{6T_{\rm kd}}{5m_{\chi^0}}}\tau_{\rm kd}\ln\left(\frac{\tau_{\rm eq}}{\tau_*}\right), \quad \tau_* = 1.05\tau_{\rm kd}$$

- long after the matter radiation equality

$$k_{\rm fs} \simeq 3.5\,/{\rm pc} > 1/\tau_{\rm kd} \simeq 0.11\,/{\rm pc}$$

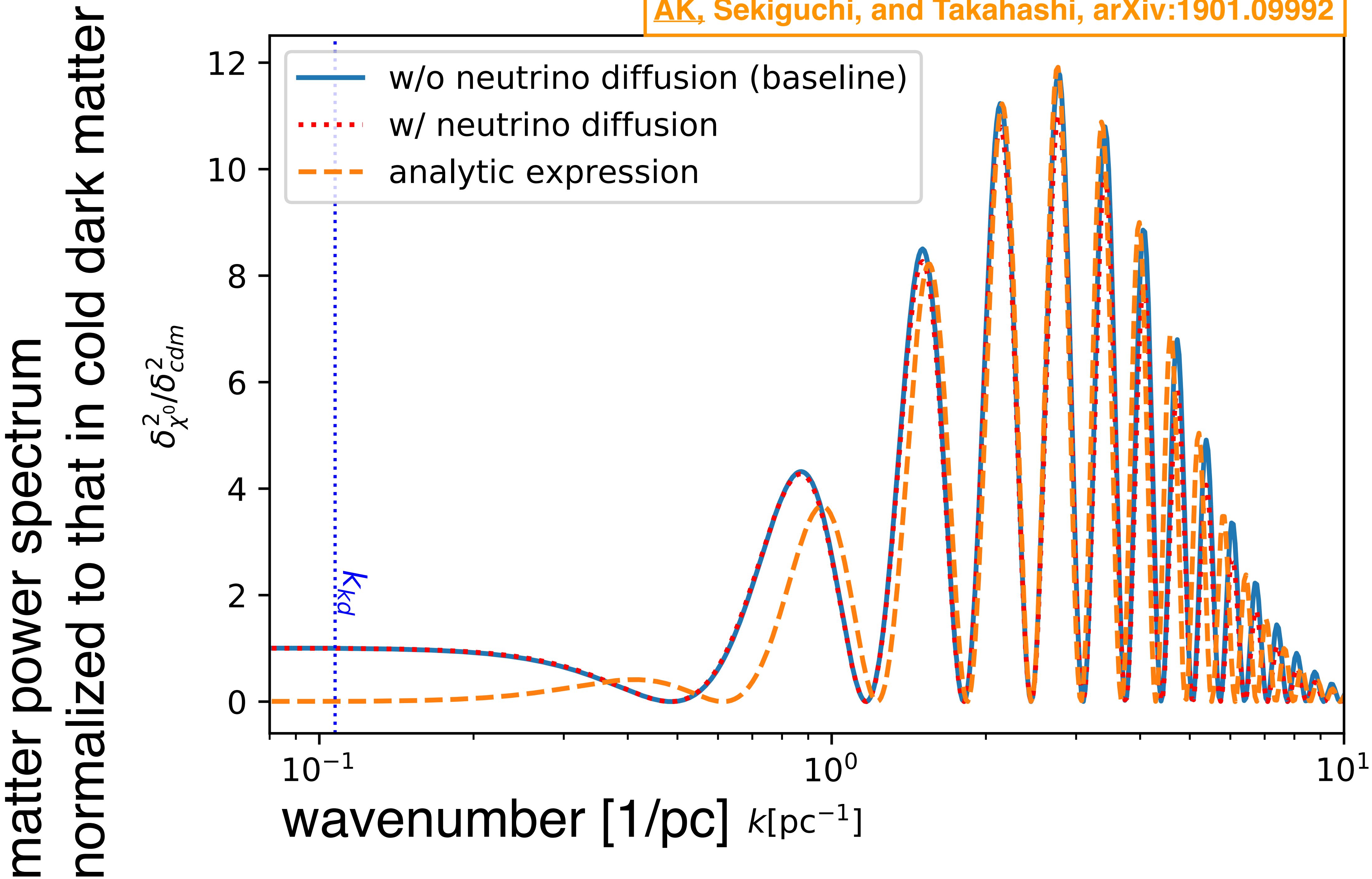
$$M_{\rm fs} \simeq 1.0\times 10^{-7}\,M_\odot < M_{\rm kd} \simeq 1.1\times 10^{-4}\,M_\odot$$

$$M_{\rm kd} = \frac{4\pi}{3}\rho_{\chi,0}\tau_{\rm kd}^3$$

$$M_{\rm fs} = \frac{4\pi}{3}\rho_{\chi,0}\left(\frac{\pi}{k_{\rm fs}}\right)^3$$

Neutrino diffusion

AK, Sekiguchi, and Takahashi, arXiv:1901.09992



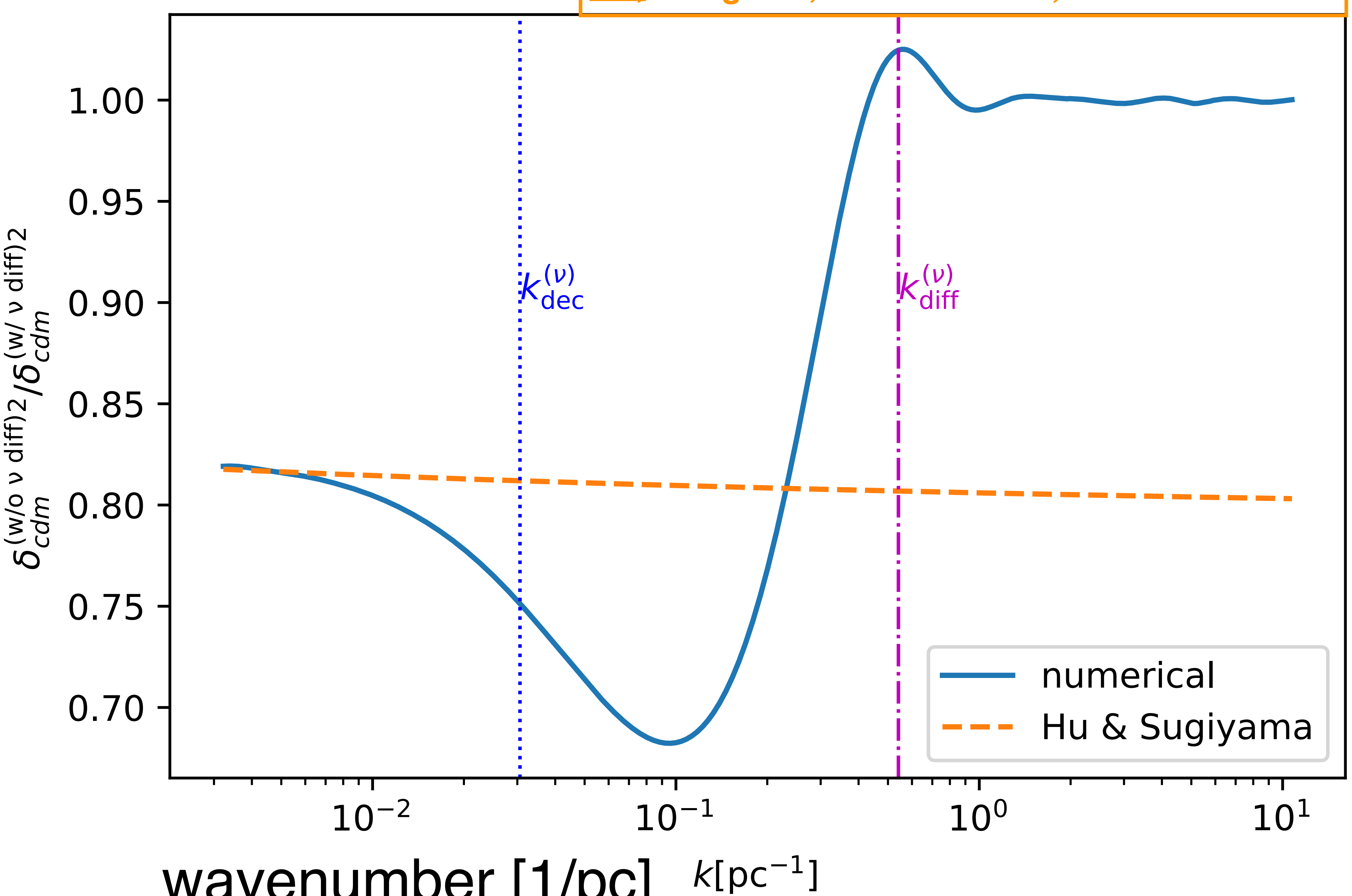
Neutrino diffusion is not important for the ratio $\delta^2_{\chi^0}/\delta^2_{\mathrm{cdm}}$

Neutrino diffusion

Cold dark matter w/ and w/o neutrino diffusion

AK, Sekiguchi, and Takahashi, arXiv:1901.09992

matter power spectrum w/o neutrino diffusion normalized to that w/ neutrino diffusion



wavenumber [1/pc]

Neutrino diffusion changes the power spectrum up to 30%

Halo profile

Navarro-Frenk-White (NFW) profile: $\rho = \dfrac{\rho_s}{(r/r_s)(1+r/r_s)^2}$

Navarro, Frenk, and White, ApJ, 1996

Navarro, Frenk, and White, ApJ, 1997

$$\left(\rho_s,\ r_s\right) \leftrightarrow \left(c = r_{200}/r_s,\ M = M_{200}\right) \rightarrow \bar{L} = Mc^3/f(c)^2$$

$f(c) = \ln(1+c) - c/(1+c)$ - normalization does not matter

c-M relation

- case 1: power law - more sensitive to the smallest halos

$$c_{200} = 7.80 \left(\frac{M_{200}}{10^{12}\, M_\odot/h}\right)^{-0.08} \left[1 + 0.2\left(\frac{M_{200}}{10^{15}\, M_\odot/h}\right)^{1/2}\right]$$

Gao, Frenk, Jenkins, Springel, and White, MNRAS, 2012

Prada, Klypin, Cuesta, BetancortRijo, and Primack, MNRAS, 2012

- case 2: flattening toward smaller halos

Diemand, Moore, and Stadel, Nature, 2005 … Sanchez-Conde and Prada, MNRAS, 2012

$$c_{200} = \sum_{i=0}^{5} c_i \left[\ln\left(\frac{M_{200}}{M_\odot/h}\right)\right]^i$$

$$c_i = \{37.5153,\ -1.5093,\ 1.636\times 10^{-2},\ 3.66\times 10^{-4},\ -2.89237\times 10^{-5},\ 5.32\times 10^{-7}\}$$

Subhalo mass function

Cold dark matter subhalo mass function:

$$\frac{dn_{\rm sub}}{dm} = \frac{A}{M}\left(\frac{m}{M}\right)^{-\alpha}, \quad A : \int_{10^{-5}M}^{10^{-2}M} dm\, m \frac{dn_{\rm sub}}{dm} = 0.1$$

Springel, Wang, Vogelsberger, Ludlow, Jenkins, Helmi, Navarro, Frenk, and White, MNRAS, 2008

$(\alpha, A) = (1.9, 0.0318)$ Diemand, Kuhlen, and Madau, ApJ, 2007 Madau, Diemand, and Kuhlen, ApJ, 2008

$(2.0, 0.0145)$ - more sensitive to the smallest halos

Wino subhalo mass function:

$$\frac{dn_{\rm sub}}{dm} \to \frac{dn_{\rm sub}}{dm} \times \left.\frac{(dn/d\ln M)_\chi}{(dn/d\ln M)_{\rm cdm}}\right|_{\rm PS}$$ and $m_{\rm min} = 0$

(for comparison, $\frac{dn_{\rm sub}}{dm}$ as it is and $m_{\rm min} = M_{\rm kd} \simeq 1.1 \times 10^{-4} M_\odot$)

Subhalo mass function

Modified Press-Schechter: $$\frac{dn}{d\ln M} = \frac{\rho_{\chi,0}}{M} f(\nu) \frac{d\ln\nu}{d\ln M}$$

$$f(\nu) = A\sqrt{\frac{2q\nu^2}{\pi}}\left(1+(q\nu^2)^{-p}\right)\exp\left(-\frac{q\nu^2}{2}\right), \qquad \nu = \frac{\delta_c}{D(z)\sigma(M)}$$

- growth factor $D(0) = 1$

Ellipsoidal collapse: $A = 0.3222\,,\ p = 0.3\,,\ q = 1$

Sheth and Tormen, MNRAS, 1999

Leo, Baugh, Li, and Pascoli, JCAP, 2018

Smooth-k filter: $$\sigma^2(M) = \int_0^\infty d\ln k \frac{k^3}{2\pi^2} P(k) W^2(k;M)$$

$$W(k;M) = (1+(kR)^{\hat{\beta}})^{-1}\,,\ M = \frac{4\pi}{3}\rho_{m,0}(\hat{c}R)^3\,, \qquad \hat{\beta} = 4.8\,,\ \hat{c} = 3.30$$

- match to simulation results for matter power spectrum with dark acoustic oscillation

Subhalo mass function

Modified Press-Schechter: $$\frac{dn}{d\ln M} = \frac{\rho_{\chi,0}}{M} f(\nu) \frac{d\ln\nu}{d\ln M}$$

$$f(\nu) = A\sqrt{\frac{2q\nu^2}{\pi}}\left(1 + (q\nu^2)^{-p}\right)\exp\left(-\frac{q\nu^2}{2}\right), \quad \nu = \frac{\delta_c}{D(z)\sigma(M)}$$

- growth factor

$D(0) = 1$

Ellipsoidal collapse: $A = 0.3222\,,\ p = 0.3\,,\ q = 0.707$

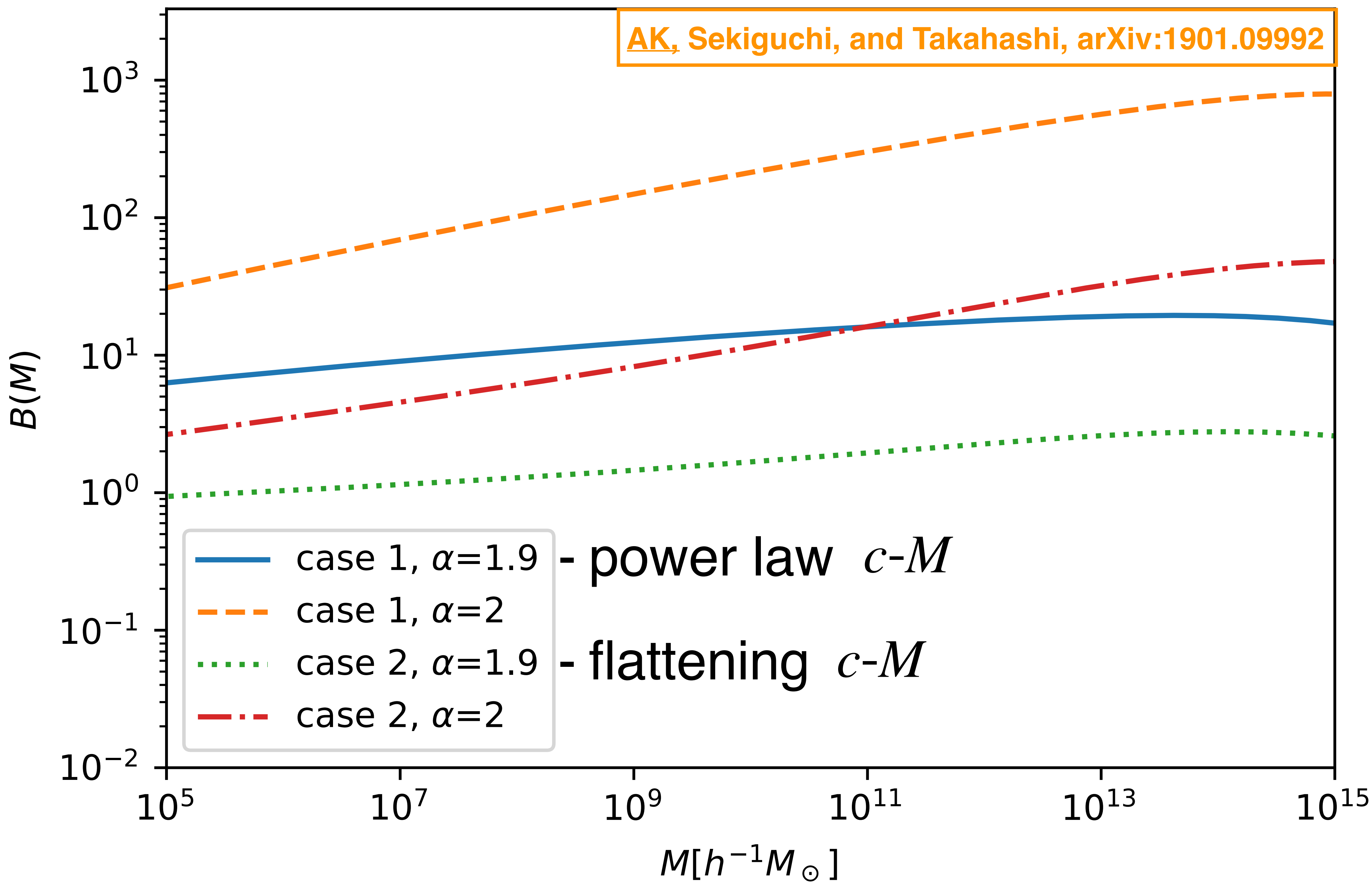
Sheth and Tormen, MNRAS, 1999

(Real-space) top-hat filter: $$\sigma^2(M) = \int_0^\infty d\ln k \frac{k^3}{2\pi^2} P(k) W^2(k;M)$$

$$W(k;M) = \frac{3(\sin(kR) - kR\cos(kR))}{(kR)^3}\,,\ M = \frac{4\pi}{3}\rho_{m,0}R^3$$

Estimated boost factor

Without B_{sub}



Estimated boost factor

Smooth-k filter:

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 $m_{\rm min} = M_{\rm kd}$

(Real-space) top-hat filter:

5.4 and 12.5 (1.7 and 3.5)

Without $B_{\rm sub}$

Smooth-k filter:

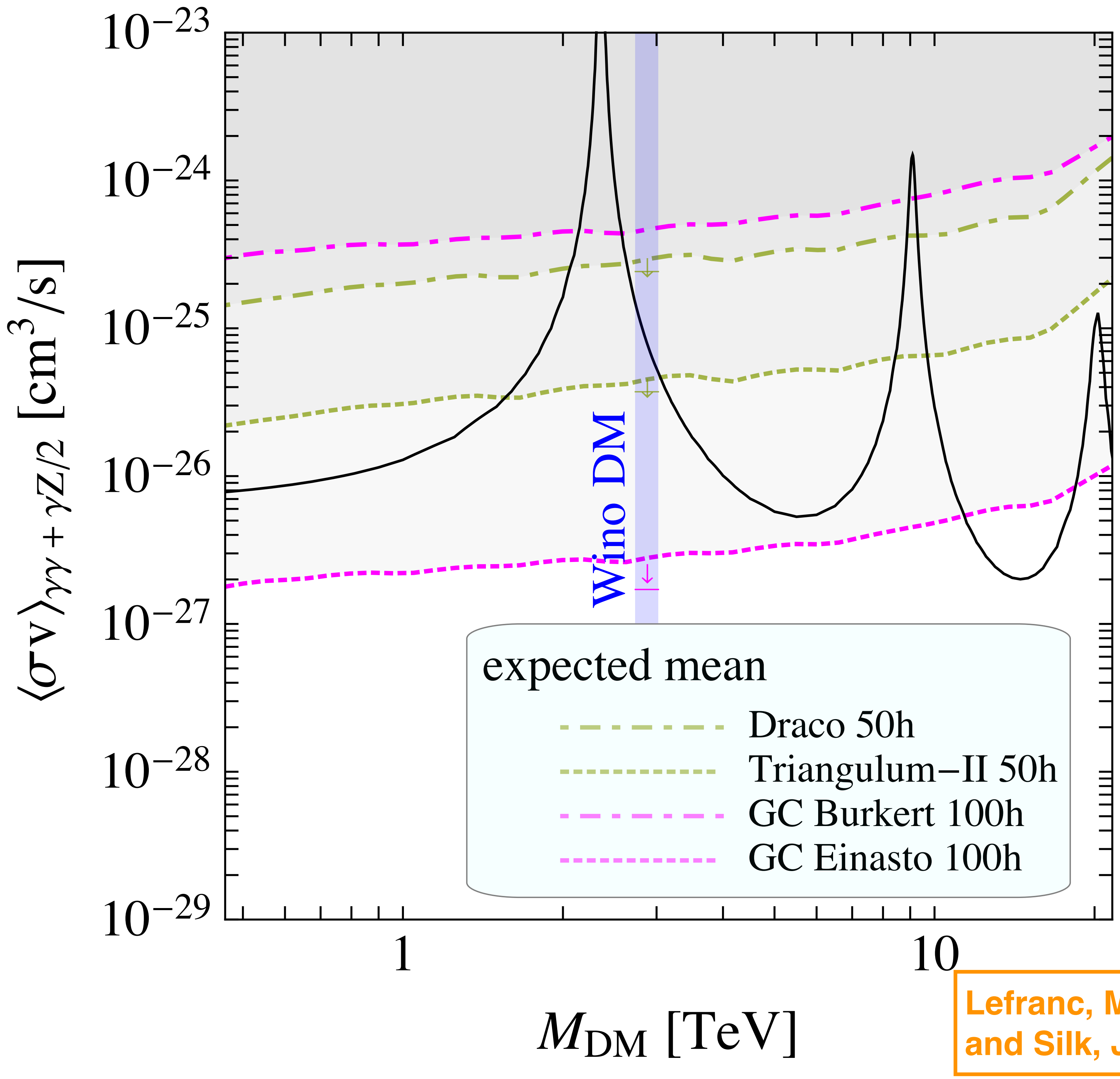
2.8 and 7.5 (1.2 and 2.5)

(Real-space) top-hat filter:

3.2 and 10.3 (1.2 and 2.7)

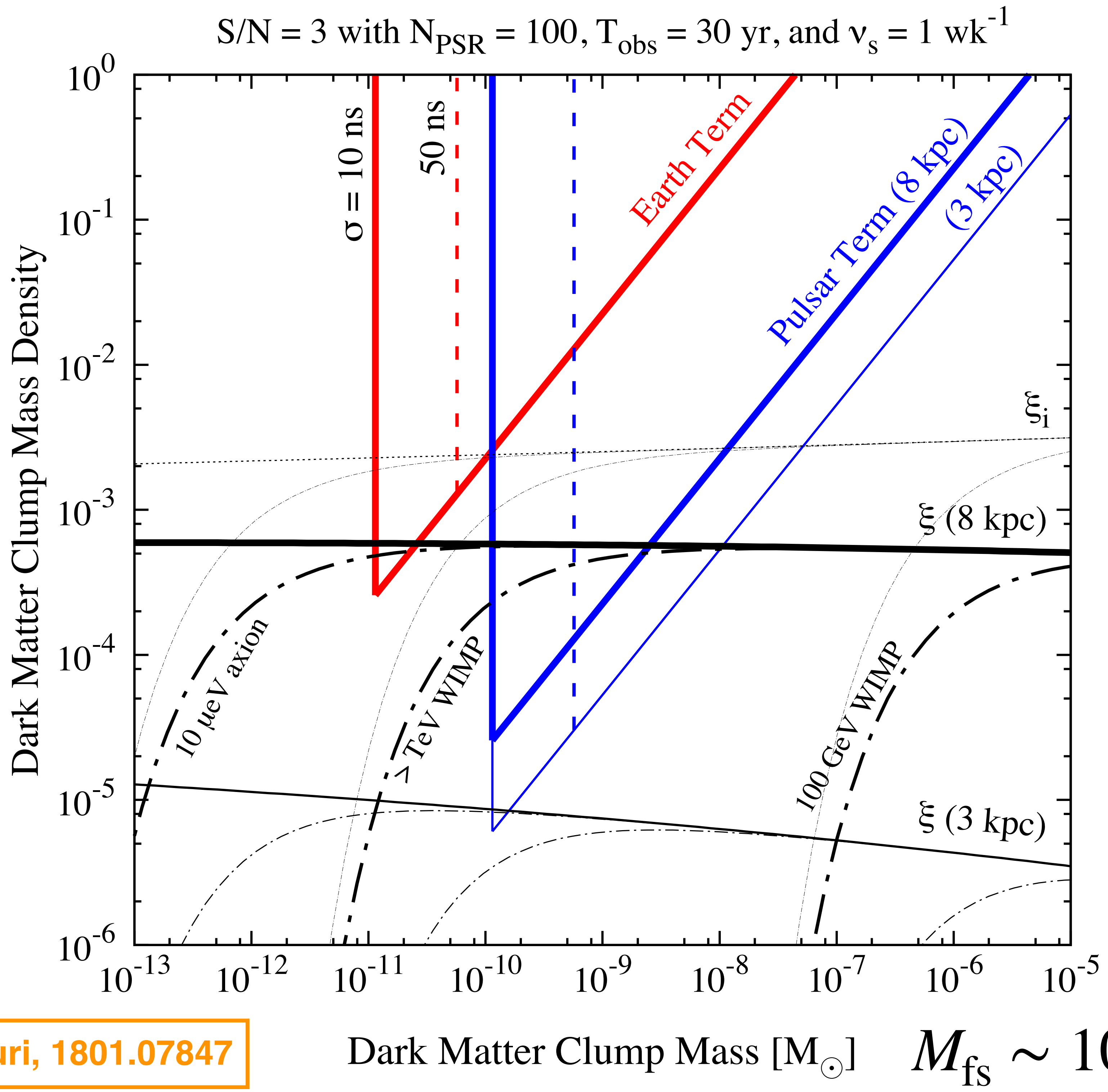
Indirect detection

CTA sensitivities



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

Detectability of small-size clump



Kashiyama and Oguri, 1801.07847

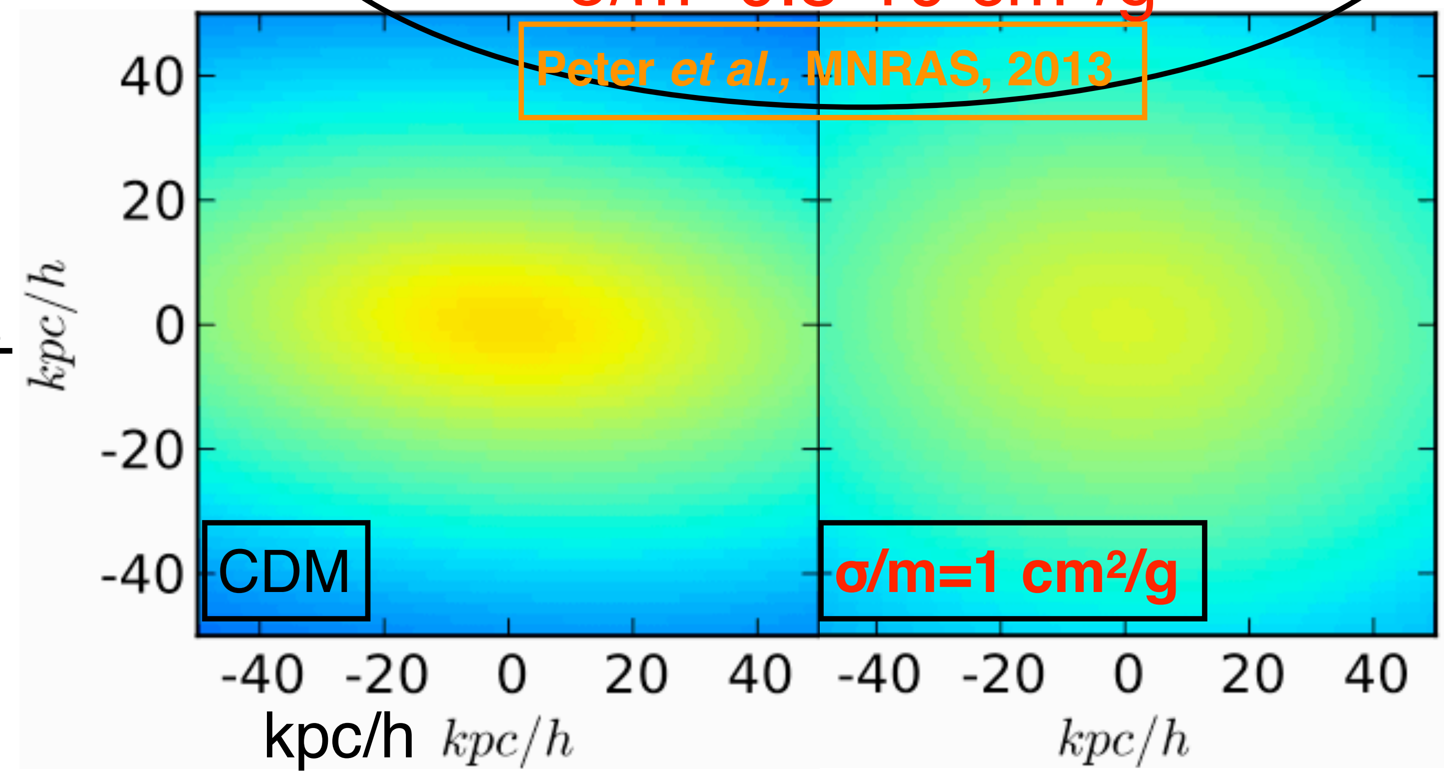
$M_{fs} \sim 10^{-7} M_\odot$

Detection of dark matter clump encounter with the Earth or a pulsar in pulsar timing array data

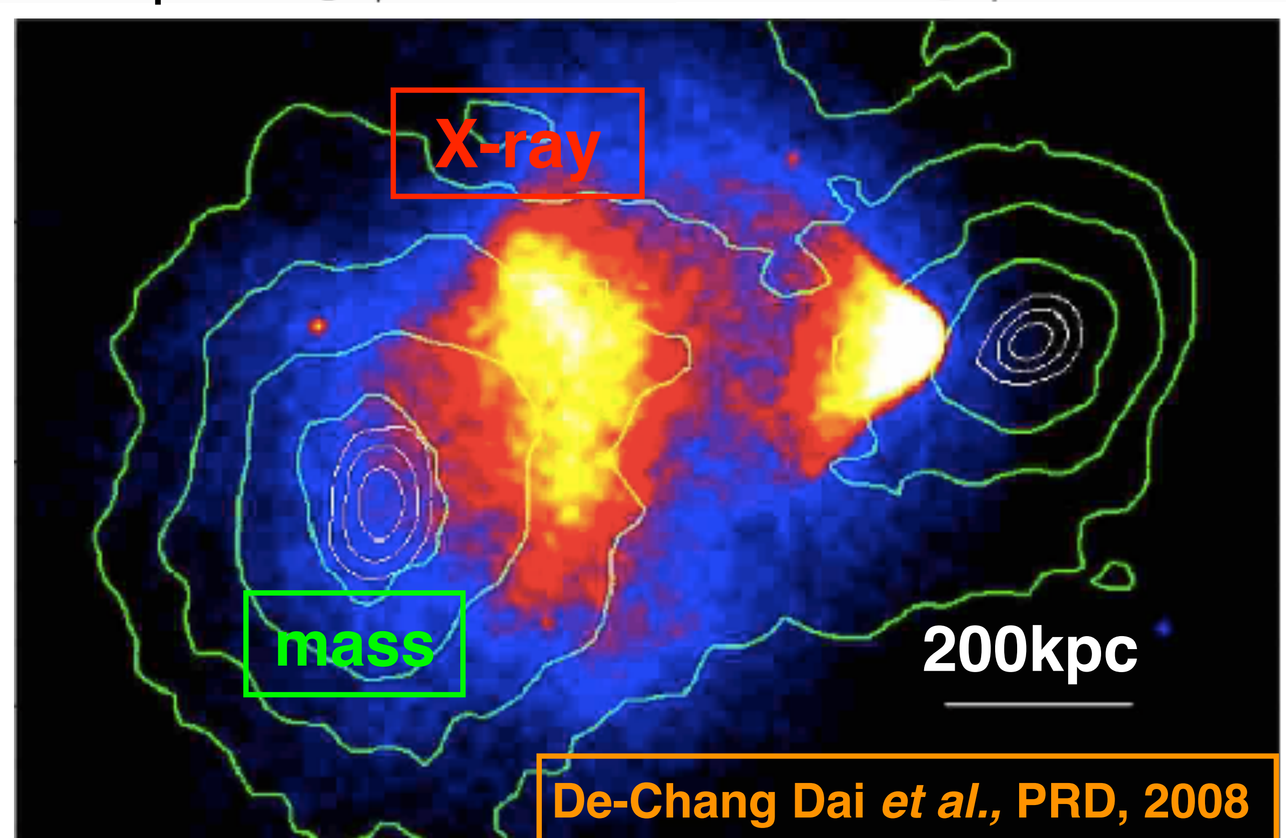
Constraints from galaxy clusters

V_{max}~1000 km/s
↔ galaxy: V_{max}~100 km/s
σ/m=0.5-10 cm^2/g

Halo shape - ellipticity
- galaxy cluster MS 2137–23
(e=0.18@r=70 kpc)
(estimate) σ/m<0.02 cm^2/g
Miralda-Escudé *et al.*, ApJ, 2002
(simulation/l.o.s. effect)
σ/m<1 cm^2/g
Peter *et al.*, MNRAS, 2013



Bullet cluster - transparency
- 1E0657-558
(offset) σ/m<1.25 cm^2/g
(massloss) σ/m<0.7 cm^2/g
Randall *et al.*, ApJ, 2008
- an ensemble (72)
(offset) σ/m<0.47 cm^2/g
Harvey *et al.*, Science, 2015

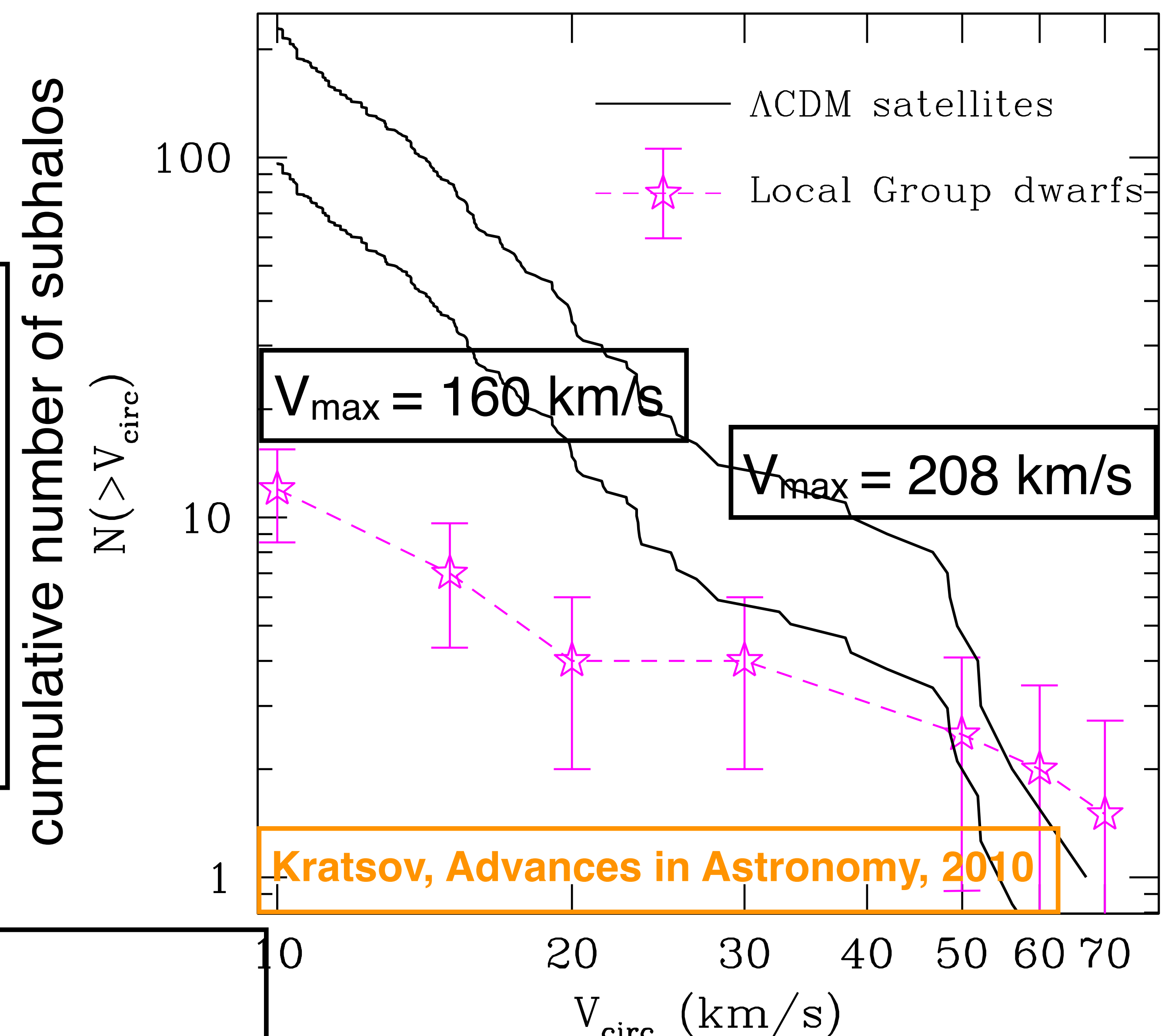


Small scale crisis I

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

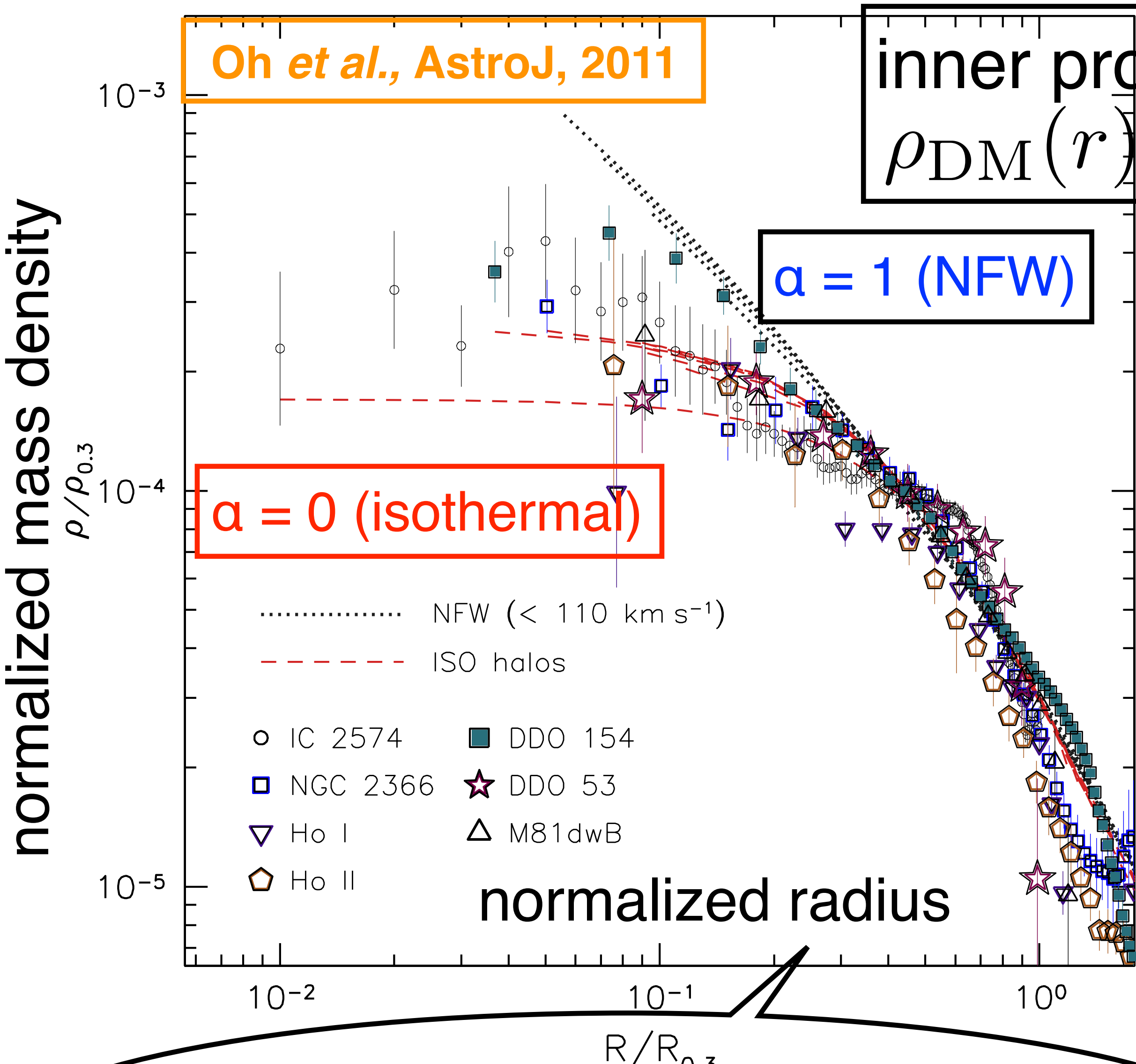
(maximum) circular velocity

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

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

field dwarf spheroidal galaxies
~10^9 Msun

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

NFW profile:

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

isothermal profile:

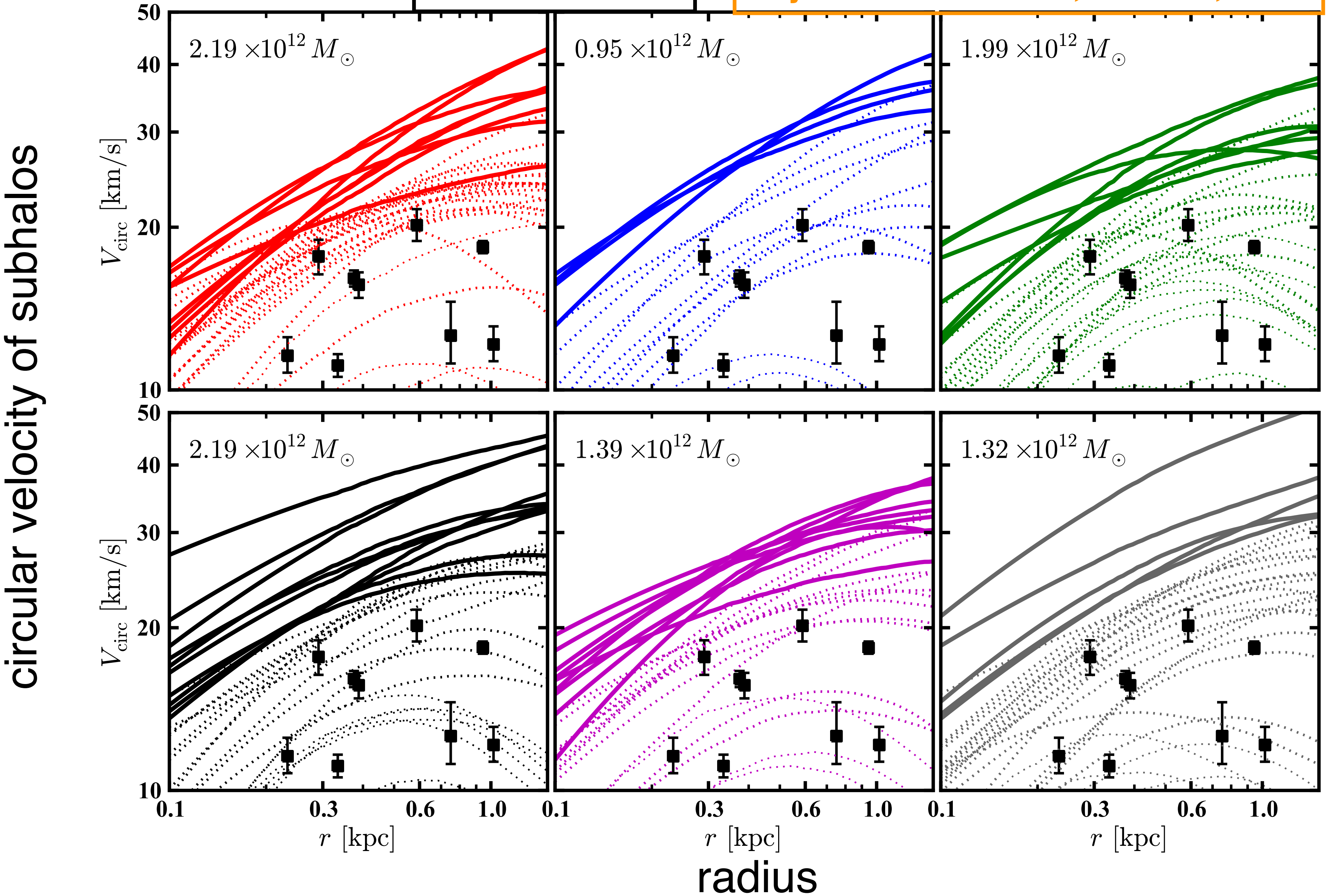
$$\rho_{\rm DM}(r) = \rho_{\rm DM}^0 \begin{cases} 1 & (r \ll r_0) \\ (r_0/r)^2 & (r \gg r_0) \end{cases}$$

Small scale crisis III

too big to fail problem

MW-like halos

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



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

Concentration-mass relation

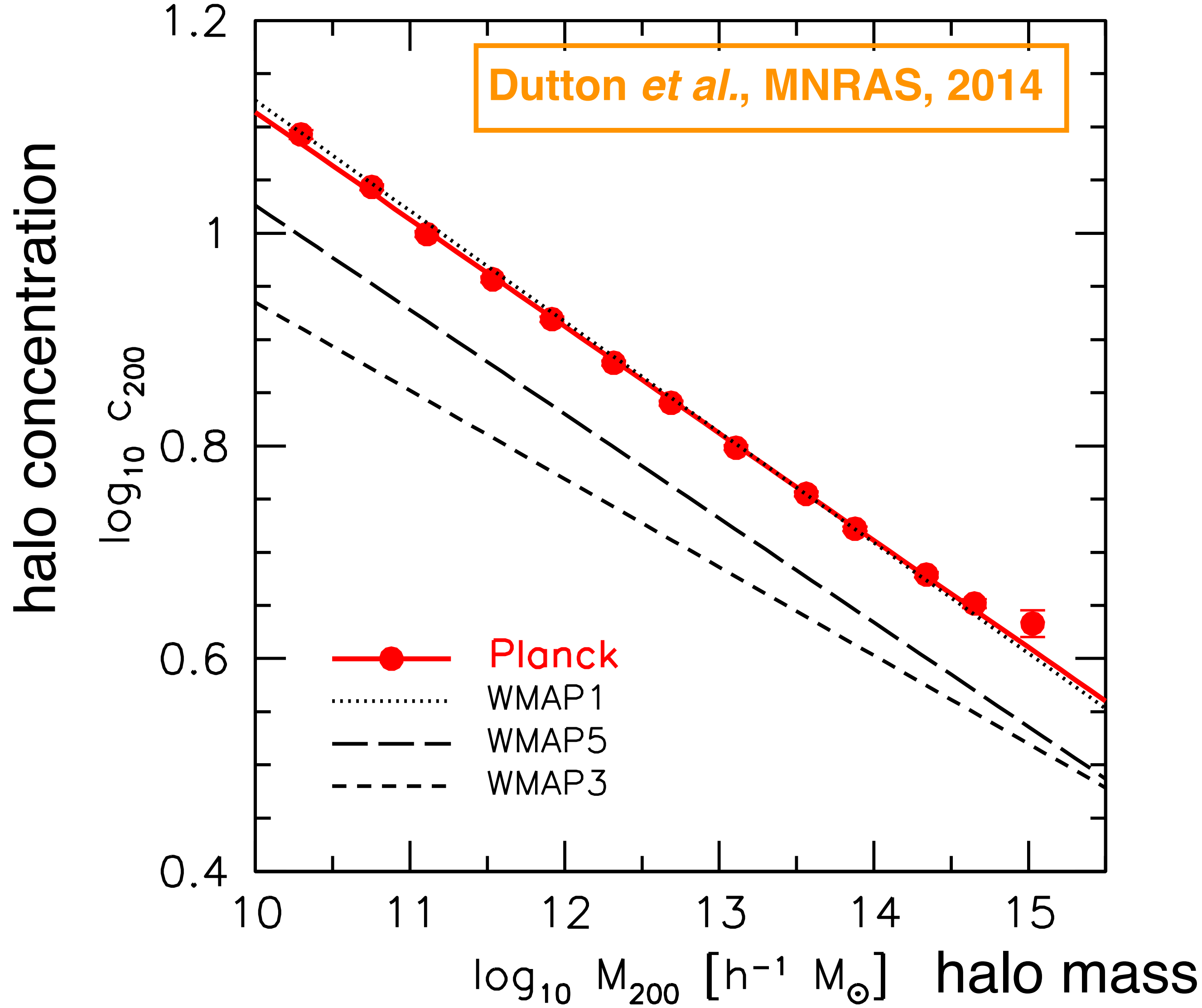
Why is a simulated rotation curve (almost) **DEFINITE** for a given V_{max}?
Two parameters for the NFW profile

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

A relation between two parameters usually given as the **CONCENTRATION-MASS RELATION**

$$c_{200} = 10^{0.905\pm0.11}(M_{200}/10^{12}\,h^{-1}\,M_\odot)^{-0.101}$$

small intrinsic scatter

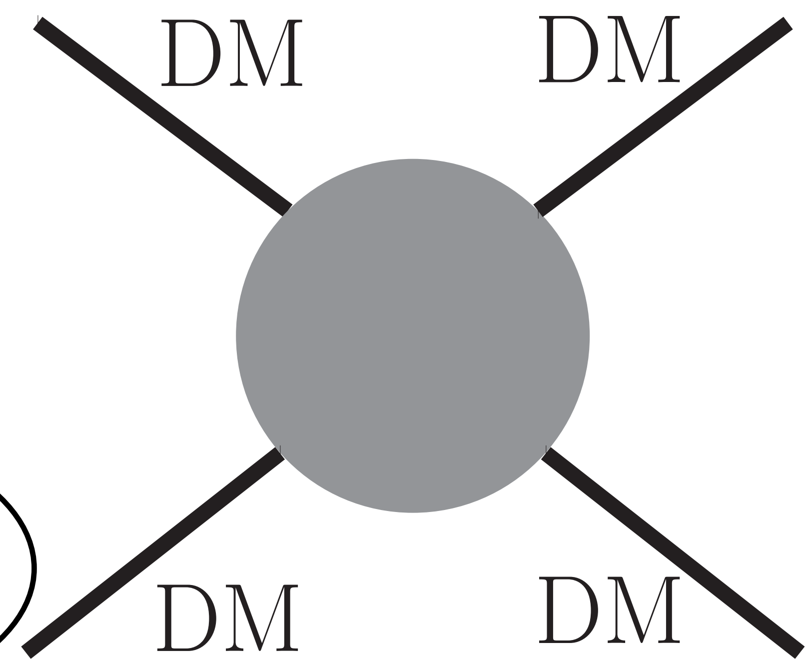


$$c_{200} = r_{200}/r_s$$

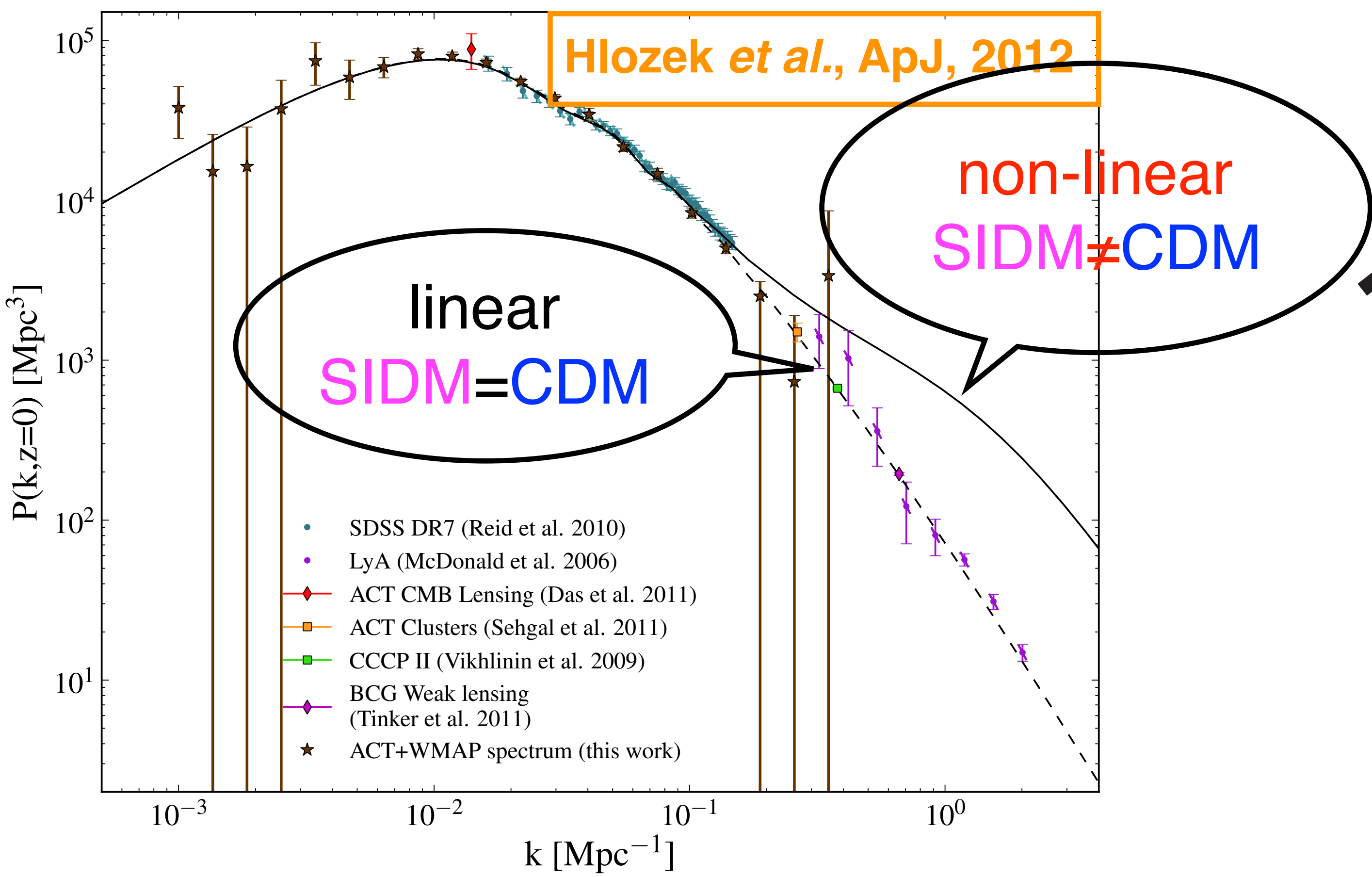
$$M_{200}(< r_{200}) = \frac{4\pi}{3}\bar{\rho}_{\rm M} r_{200}^3$$

Dark matter self-interaction

Self-Interacting Dark Matter: SIDM



power spectrum of density perturbations



wave number

Reaction rate $\Gamma = \sigma v \rho / m$
σ: cross section
v: relative velocity
ρ: dark matter mass density
m: dark matter mass

SIDM structure formation starts with
the same linear (initial) matter power spectra as CDM,
but self-interactions become important
as structure formation proceeds ↔ ρ increases

SIDM halo - velocity dispersion

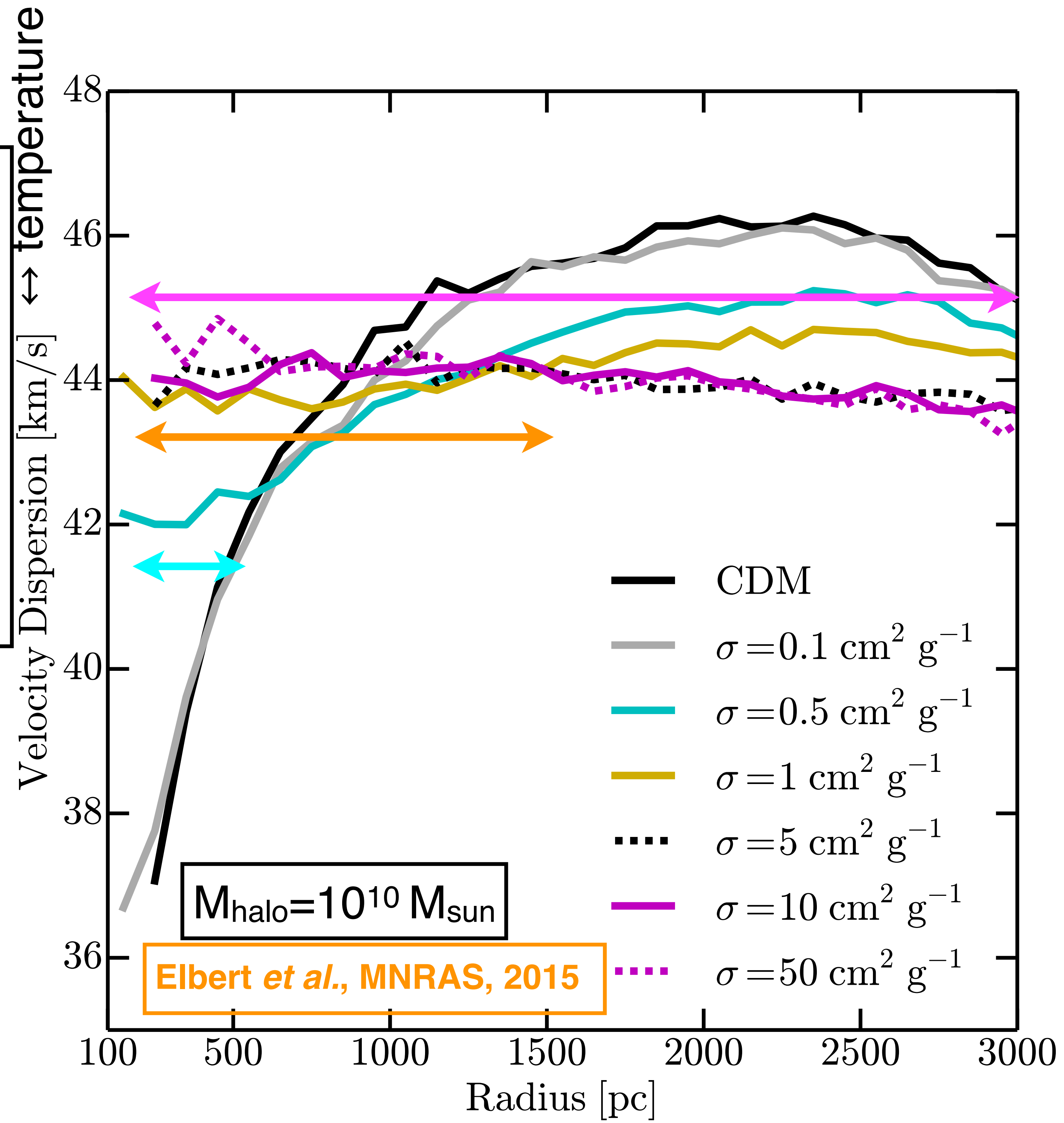
SIDM-only simulation

SIDM halos are **THERMALIZED** (isothermal) in inner region $r < r_1$, where the self-scattering is efficient $\sigma v \rho(r_1) t_{age}/m=1$

t_{age}=5 Gyr(galaxy cluster)
10 Gyr (galaxy)

If $r_1 > r_{max}$, the gravo-thermo instability is significant

$$V_{\rm circ}(r_{\rm max}) = V_{\rm max}$$

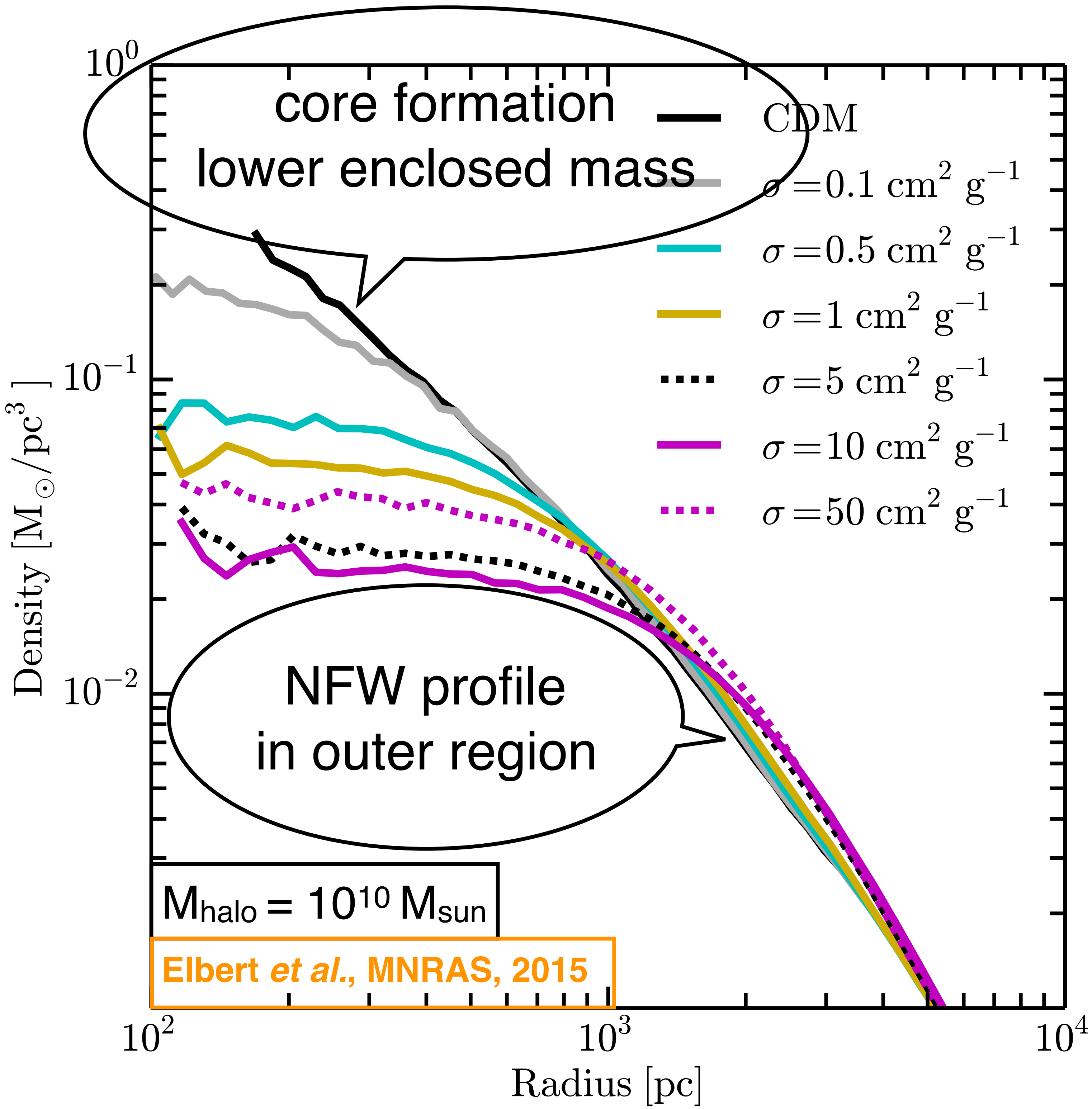


SIDM halo - mass density

SIDM-only simulation

As σ/m increases,
central density decreases

Inverted at some point
← gravo-thermo instability
↔ core-collapse

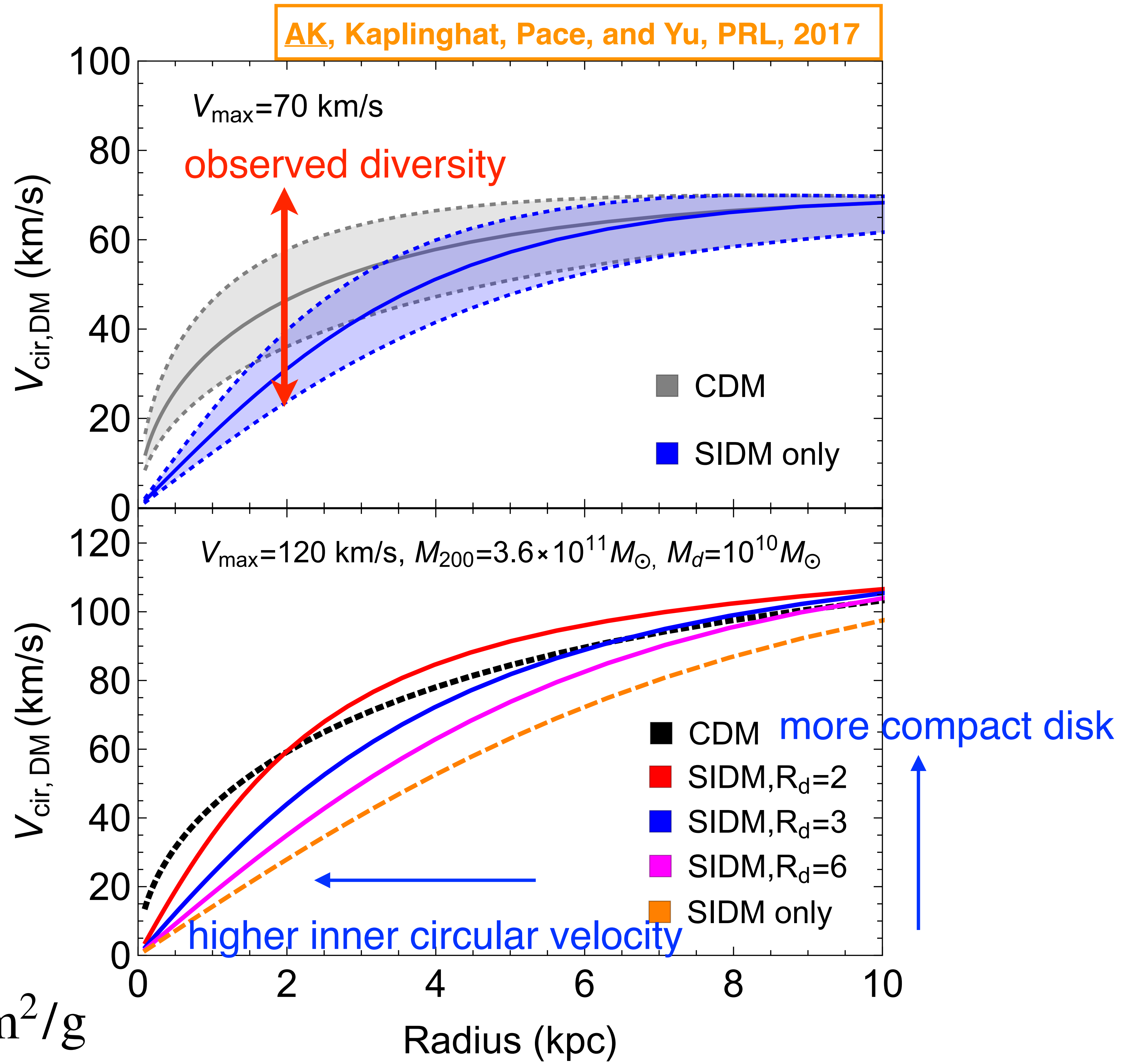


σ/m = 0.5-5 cm²/g may solve the inner mass deficit problem

Demonstration with stellar disks

- observed diversity exceeds intrinsic diversity of DM halos

- compact disk can make SIDM inner circular velocity higher than the CDM prediction

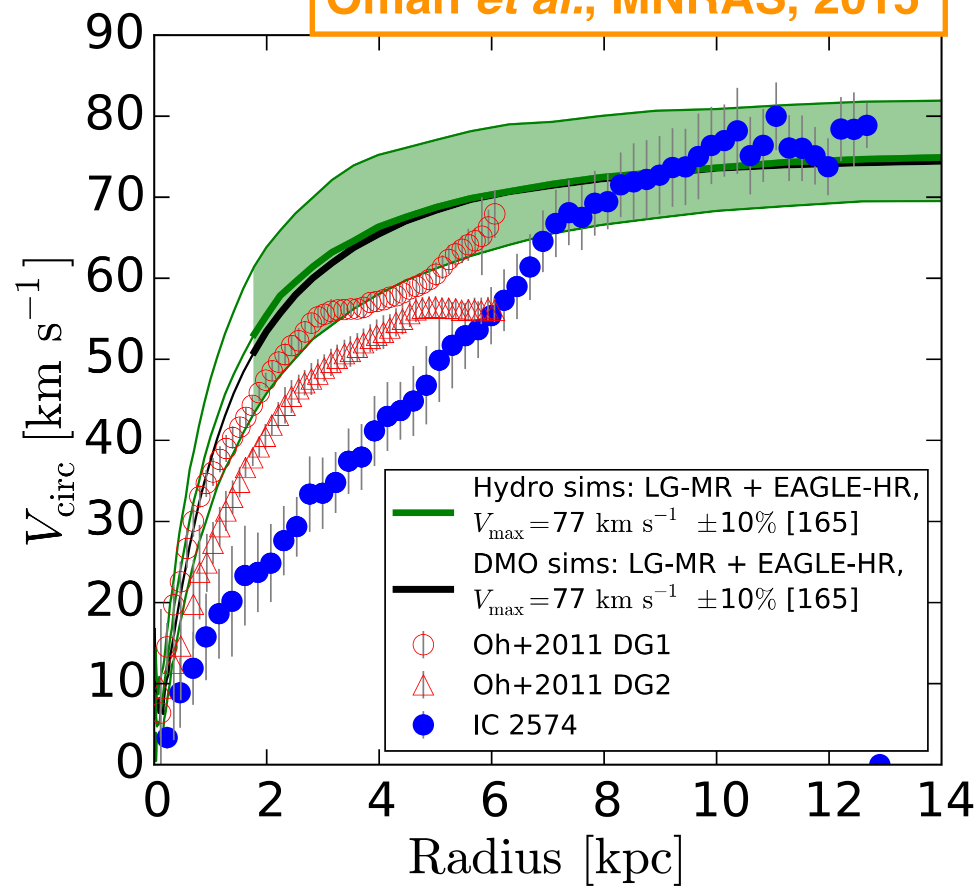


✳ Hereafter $\sigma/m = 3\,\mathrm{cm}^2/\mathrm{g}$

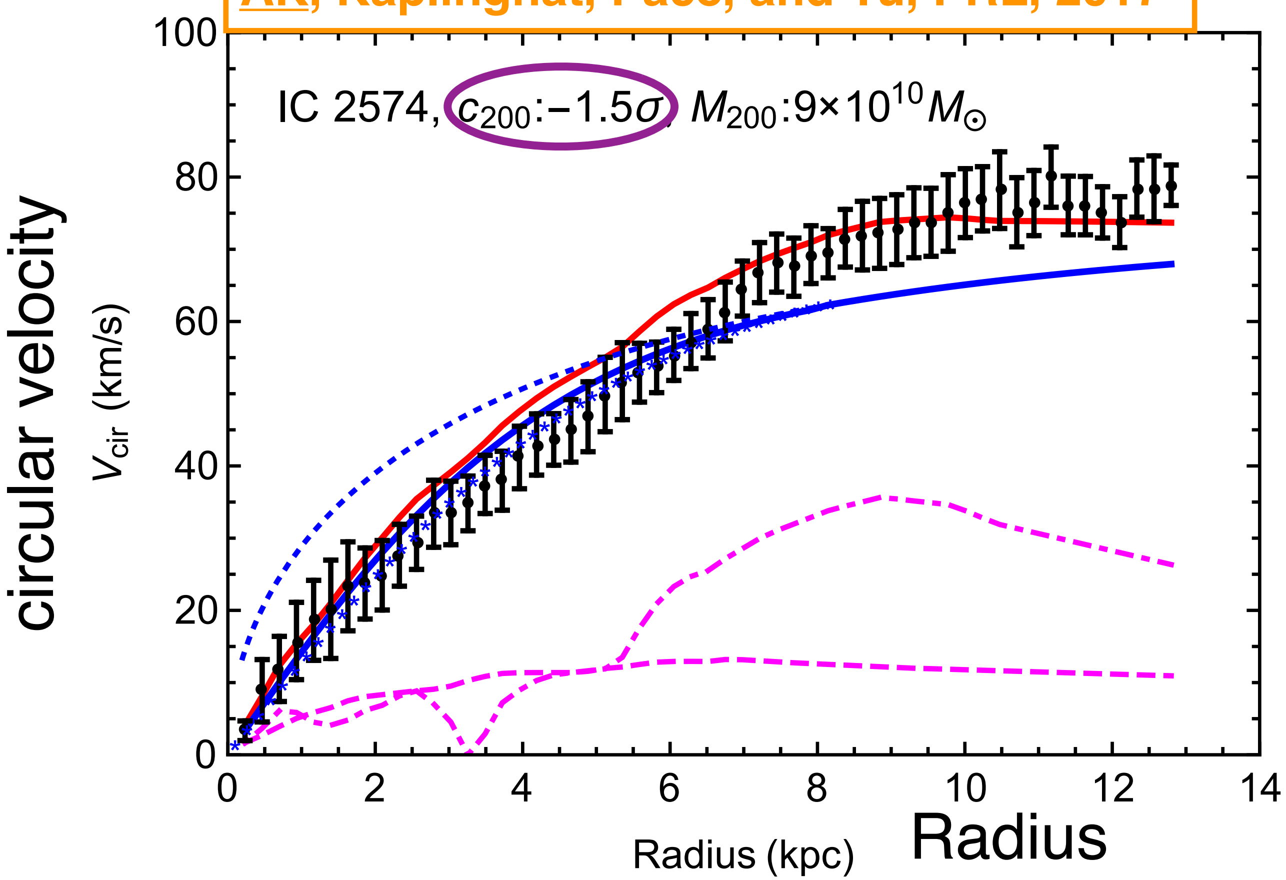
Intrinsic scatter

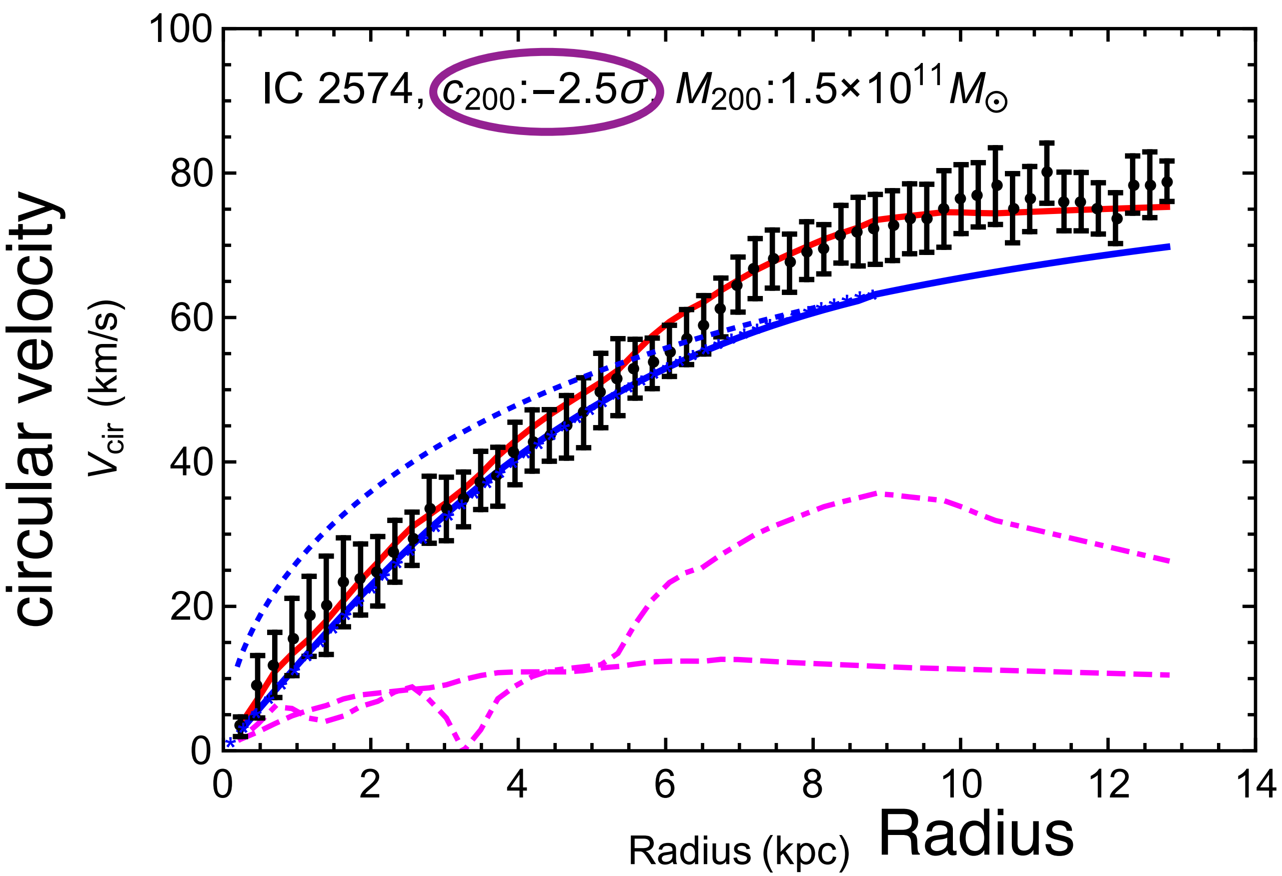
Intrinsic diversity of DM halos should be taken into account to explain the observed diversity

Oman *et al.*, MNRAS, 2015



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

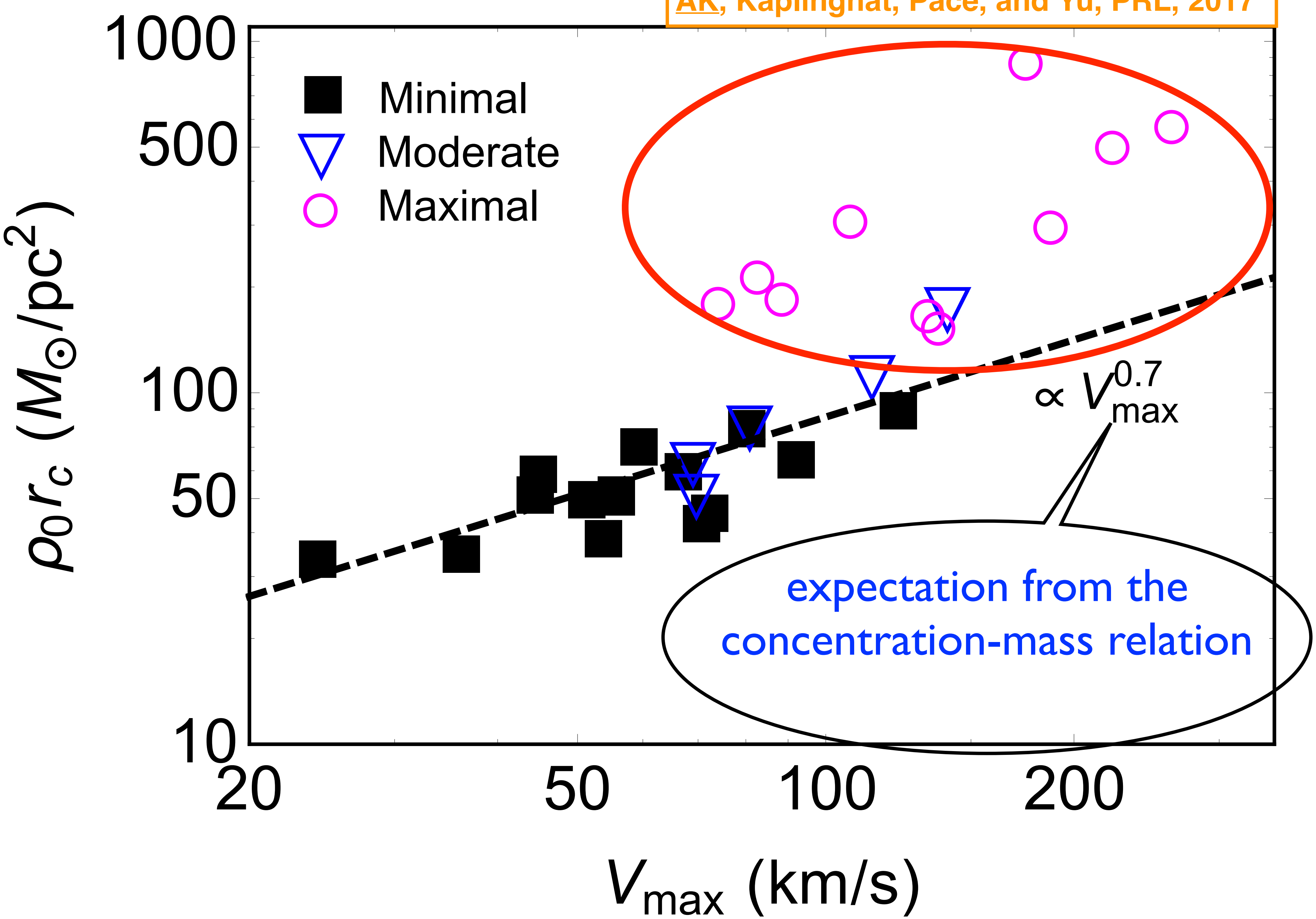




More samples

Massive spiral galaxies, **GENERALLY**, make SIDM halos **VIOLATE** the concentration-mass relation

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



Simple model

Model setup: QCD×QED-like hidden sector

- dark nucleons as DM

$$p' \sim u'u'd' \quad n' \sim u'd'd'$$

✳ discussion applies to isospin quartet DM

- small quark mass term

$$\mathscr{L}_{\rm mass} = m_{u'} u'\overline{u}' + m_{d'} d'\overline{d}'$$

→ dark pions

$$\pi'^{+} \sim u'\overline{d}' \quad \pi'^{0} \sim u'\overline{u}' - d'\overline{d}'$$

$$\pi'^{-} \sim d'\overline{u}'$$

	$SU(3)_D$	$U(1)_D$	$U(1)_{B-L+B'}$
u'	$\mathbf{3}$	$2/3$	$1/3$
$\overline{u}'$	$\overline{\mathbf{3}}$	$-2/3$	$-1/3$
d'	$\mathbf{3}$	$-1/3$	$1/3$
$\overline{d}'$	$\overline{\mathbf{3}}$	$1/3$	$-1/3$

✳ naturalness → chiral theory

- SM copy

→ harmful neutrino's

Generation and transfer of asymmetry

$U(1)_{B-L+B'} \to (-1)^{3(B-L+B')}$

Right-handed neutrinos $\overline{N}$ w/ soft breaking mass M_R

- thermal leptogenesis → $B-L$ asymmetry $T \sim M_R > 10^9\,\mathrm{GeV}$

  Fukugita and Yanagida, PLB, 1986

- see-saw mechanism → active neutrino mass $y_N LH\overline{N} \xrightarrow{\overline{N}} \frac{y_N^2}{M_R} LHLH$

- generation of the portal operator

$$y_N^2 \sim 10^{-5} \left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right)\left(\frac{M_R}{10^9\,\mathrm{GeV}}\right)$$

Scalar down quark H'_C w/ mass $M_{H'_C}$

	$SU(3)_D$	$U(1)_D$	$U(1)_{B-L+B'}$
H'_C	$\mathbf{3}$	$-1/3$	$-2/3$

$H'^{\dagger}_C \overline{u}'\overline{d}'$ $\quad H'_C \overline{d}'\overline{N}$

$$\xrightarrow{H'_C} \frac{1}{M_{H'_C}^2} \overline{u}'\overline{d}'\overline{d}'\overline{N} \qquad y_N LH\overline{N}$$

$$\xrightarrow{\overline{N}} \frac{y_N}{M_{H_C}^2 M_R} \overline{u}'\overline{d}'\overline{d}' LH$$

$U(1)_{B-L+B'}$

✗ $H'_C u'd'$ $\quad H'^{\dagger}_C d'\overline{N}$

$$\to \frac{1}{M_*^3} u'd'd'LH$$

∗ decoupling after leptogenesis $M_{H_C} \sim M_R$

Entropy transfer

$U(1)'$ breaking scalar $H^{+'}$

$$\mathscr{L}_{A'} = \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{m_{\gamma'}}{2} A'_\mu A'^\mu$$

Dark pions annihilate/decay into dark photon $m_{\gamma'} < m_{\pi'}$

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

- decay after neutrino decoupling $T \sim 1\,\mathrm{MeV} \leftrightarrow t \sim 1\mathrm{s}$

→ transferred entropy heating only e and γ

→ lower bound on $\Gamma_{\gamma' \rightarrow e\bar{e}}$

- decay before neutrino decoupling

→ thermalized dark photon heating only e and γ

→ lower bound on $m_{\gamma'}$

DM direct detection

$p' \sim\underset{\epsilon}{\times}\sim p$ interaction

- DM direct detection → upper bound on ϵ

- DM mass: $\frac{1}{M_{H'_C}^2 M_R} \bar{u}'\bar{d}'\bar{d}' LH \rightarrow \; m_{\mathrm{DM}} \simeq 8.5\,\mathrm{GeV}$ Weinberg, "Cosmology"

- $Y_{p'}/Y_{n'}$: freezes out at decoupling of conversion processes

$Y_{p'}/Y_{n'} = e^{(m_{n'} - m_{p'})/T}$ $\quad T \sim m_{\pi'}/20\text{-}30$ ↔ dark pion decoupling

$m_{n'} - m_{p'} = \mathcal{O}(m_{u'/d'})$ $\quad m_{\pi'}^2 = \mathcal{O}\left(m_{u'/d'} \Lambda_{\mathrm{QCD}'}\right)$ $\quad \rightarrow \quad Y_{p'}/Y_{n'} \sim 1$

c.f. $m_n - m_p \simeq 1.2\,\mathrm{MeV}$ $\quad m_\pi \simeq 140\,\mathrm{MeV}$ for reference

∗ if $m_{\gamma'} < B_{d'}$, dark nucleosynthesis proceeds

Krnjaic and Sigurdson, PLB. 2015…

- impacting DM direct detection

Charge of breaking scalar

Ibe, AK, Kobayashi, Kuwahara and Nakano, work in progress

$U(1)_D$ charge determines π'-$\widetilde{e}$ mixing

$SU(4)$

	$SU(3)_D$	$U(1)_D$	$U(1)_{B-L+B'}$
$\widetilde{e}$	$\mathbf{1}$	-1	0

→ Yukawa interactions $\widetilde{e}' u' \overline{d}'$ $\widetilde{e}'^{\dagger} \overline{u}' d'$

- entropy transfer through π'-$\widetilde{e}$ mixing
  + Higgs portal $|\widetilde{e}'|^2 |H|^2$

- DM direct detection through Higgs portal?

SUSY mass spectrum

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

Mini-split SUSY mass spectrum:

sfermions, heavy Higgses > 100 TeV; gravitino > 100 TeV

- 125 GeV Higgs although naturalness unanswered

gauginos ~ TeV; higgsino ~TeV

- precise $SU(5)$ grand unification
- LSP and LSP' abundance: small enough
- LSP → LSP' or vice versa long before big bang nucleosynthesis

$$\tau \sim 2 \times 10^{-3}\,\mathrm{s} \left(\frac{10^{-10}}{\epsilon}\right)^2 \left(\frac{10^3\,\mathrm{GeV}}{M_{\mathrm{light}\,S}}\right)^2$$

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

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

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

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

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

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

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

Fukuda, Matsumoto, and Mukhopadhyay, PRD, 2015

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