Composite asymmetric dark matter and galactic rotation curves

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Based on
AK, Manoj Kaplinghat, Andrew B. Pace, and Hai-bo Yu, PRL, 2017
Masahiro Ibe, AK, Shin Kobayashi, and Wakutaka Nakano, JHEP, 2018
Masahiro Ibe, AK, Shin Kobayashi, Takumi Kuwahara, and Wakutaka Nakano, JHEP, 2019

May 30, 2019 @ MITP

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

(Mini-) split supersymmetry

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

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)

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?

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

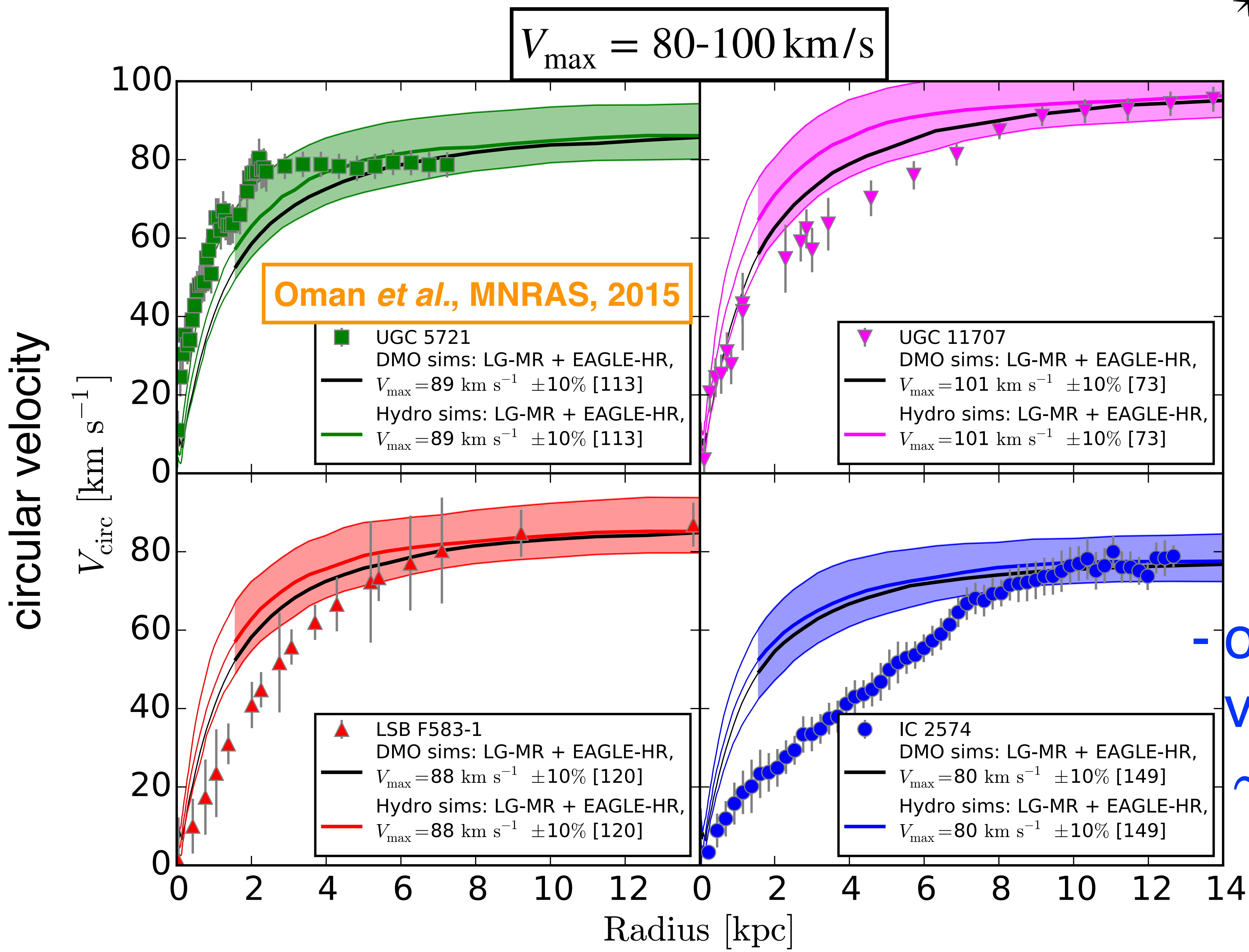
Composite asymmetric dark matter — part 2

- 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

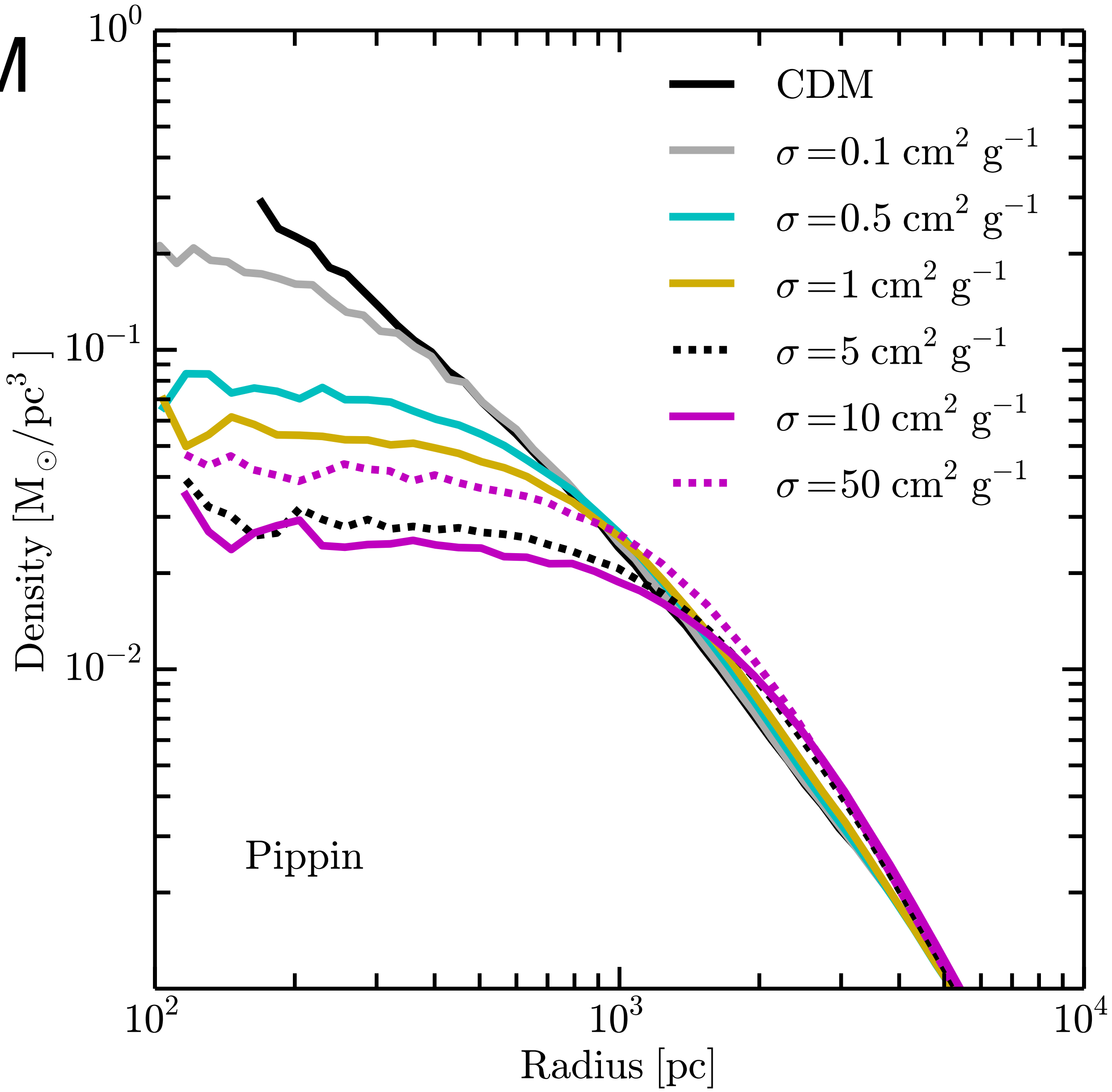
The issues may be attributed to incomplete understanding of complex astrophysical processes (subgrid physics)

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



Key observation

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

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

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

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

- inner profile is exponentially sensitive to baryon distribution

Baryons form complex objects, which show a large diversity

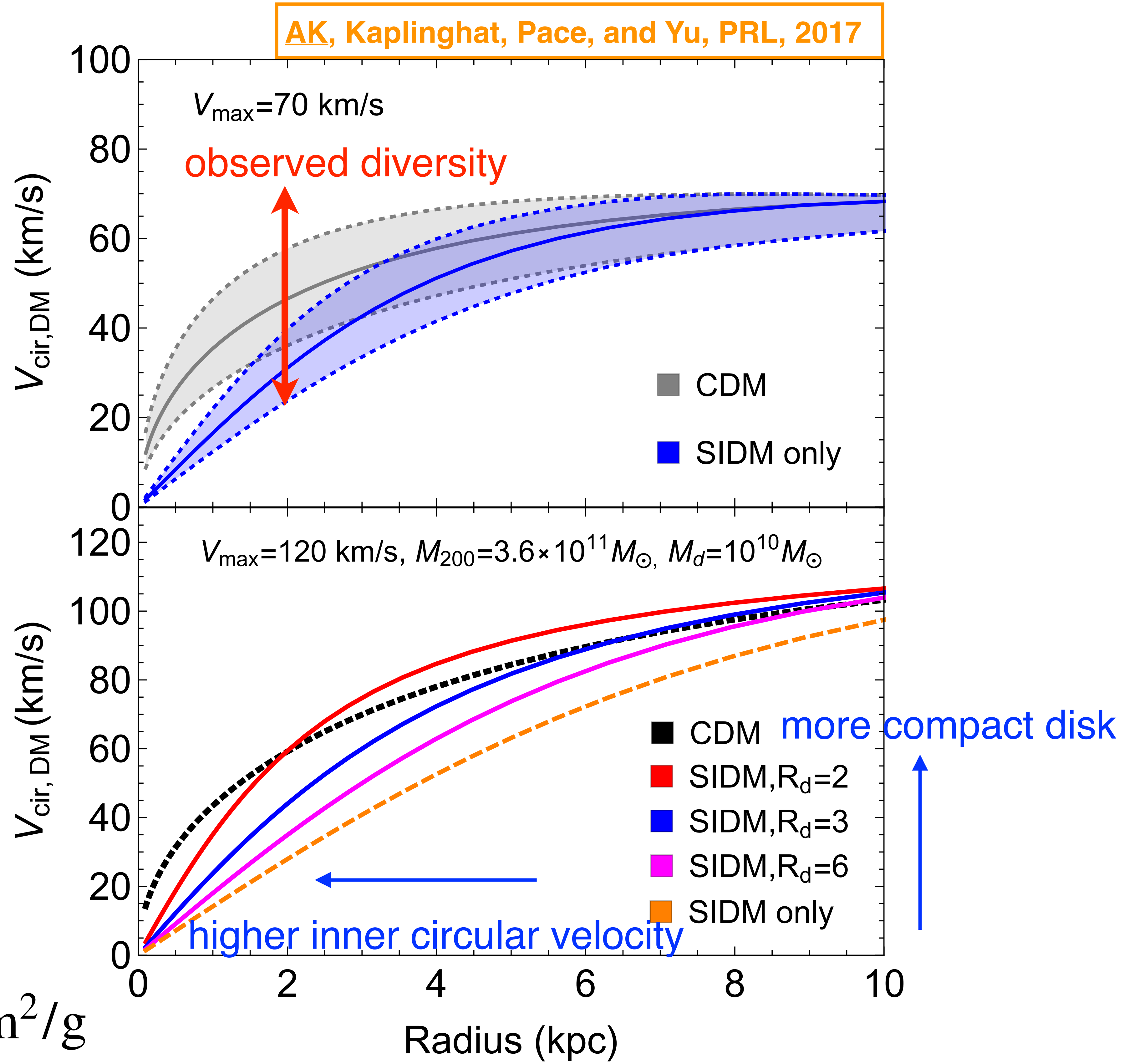
→ SIDM particles, redistributed according to formed baryonic objects, can show a diversity

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

Demonstration with stellar disks

- observed diversity exceeds intrinsic diversity of DM halos

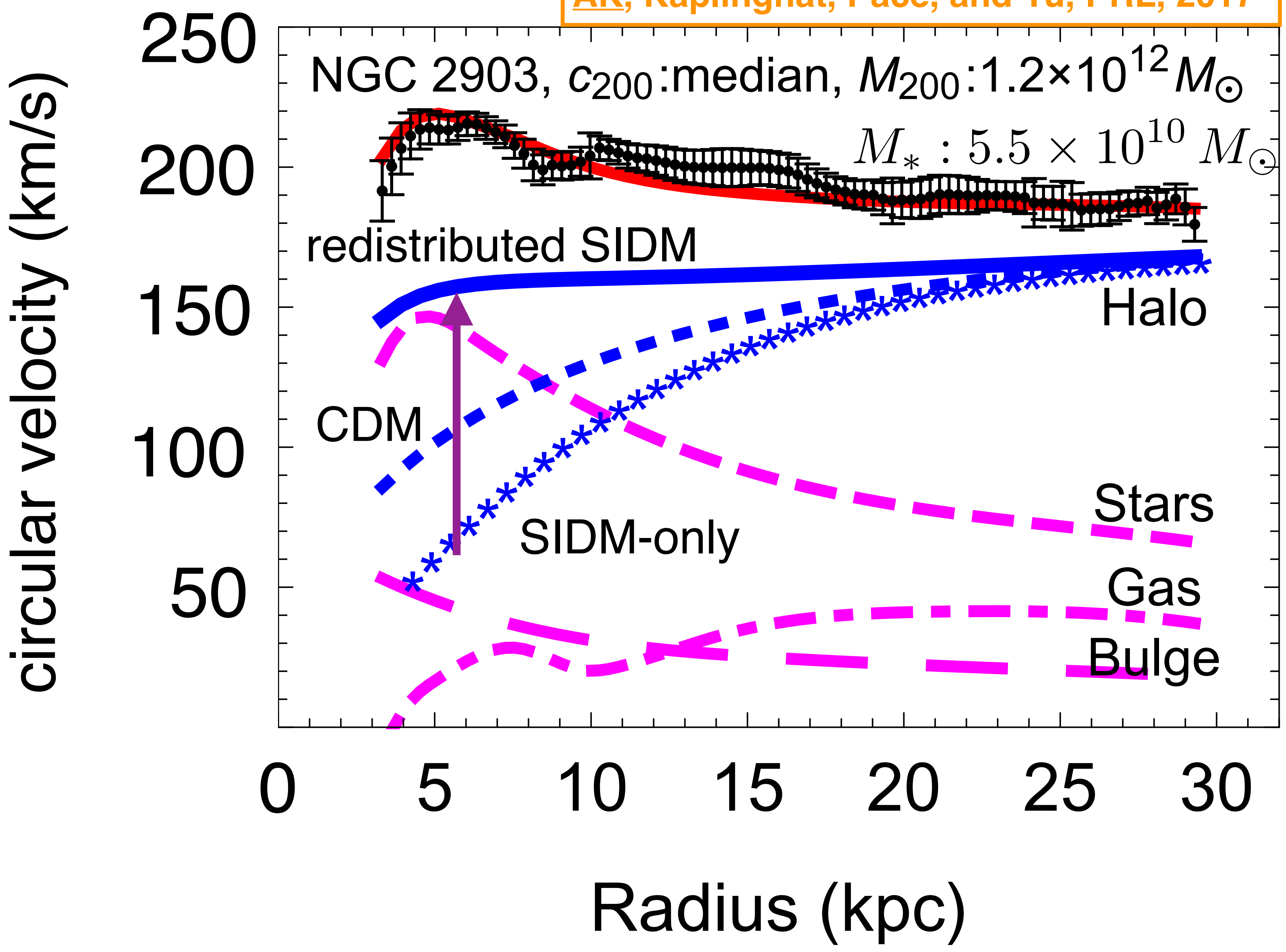
- compact disk can make SIDM inner circular velocity higher than the CDM prediction



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

Impacts in observed galaxies

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



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

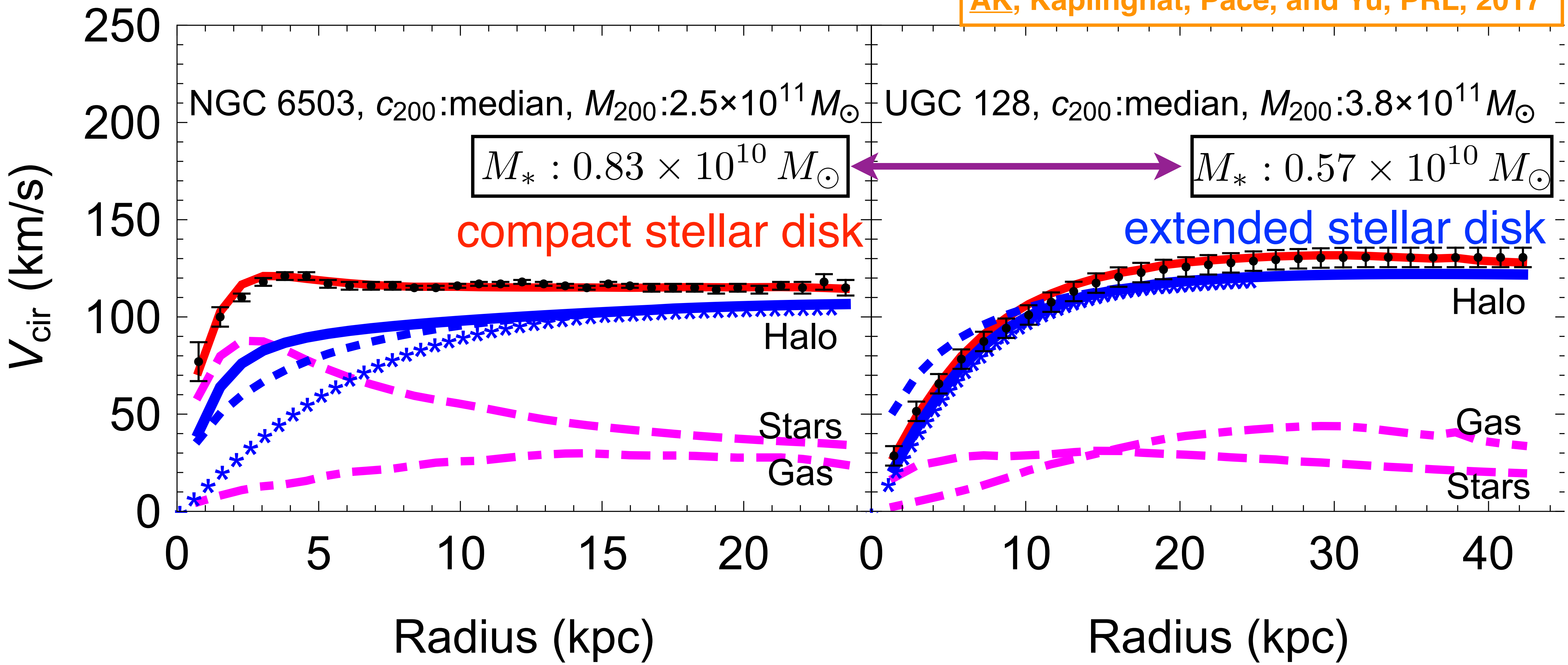
→ reproducing flat circular velocity at 10-20 kpc

Diversity in stellar distribution

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

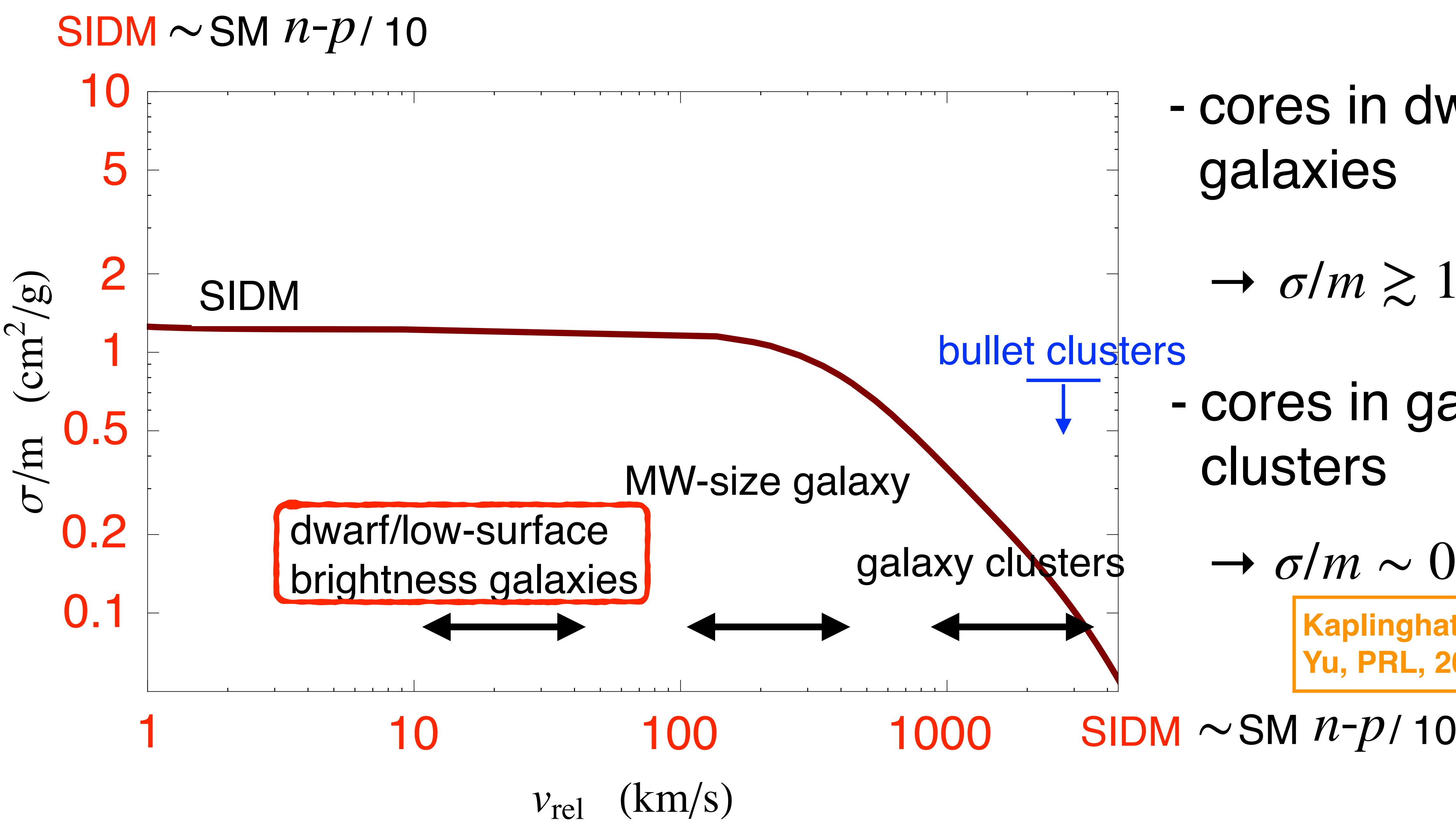
- compact → redistribute SIDM significantly
- extended → unchange SIDM distribution

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



Self-interacting dark matter

SIDM cross section indicated by small-scale puzzles



- cores in dwarf galaxies

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

- cores in galaxy clusters

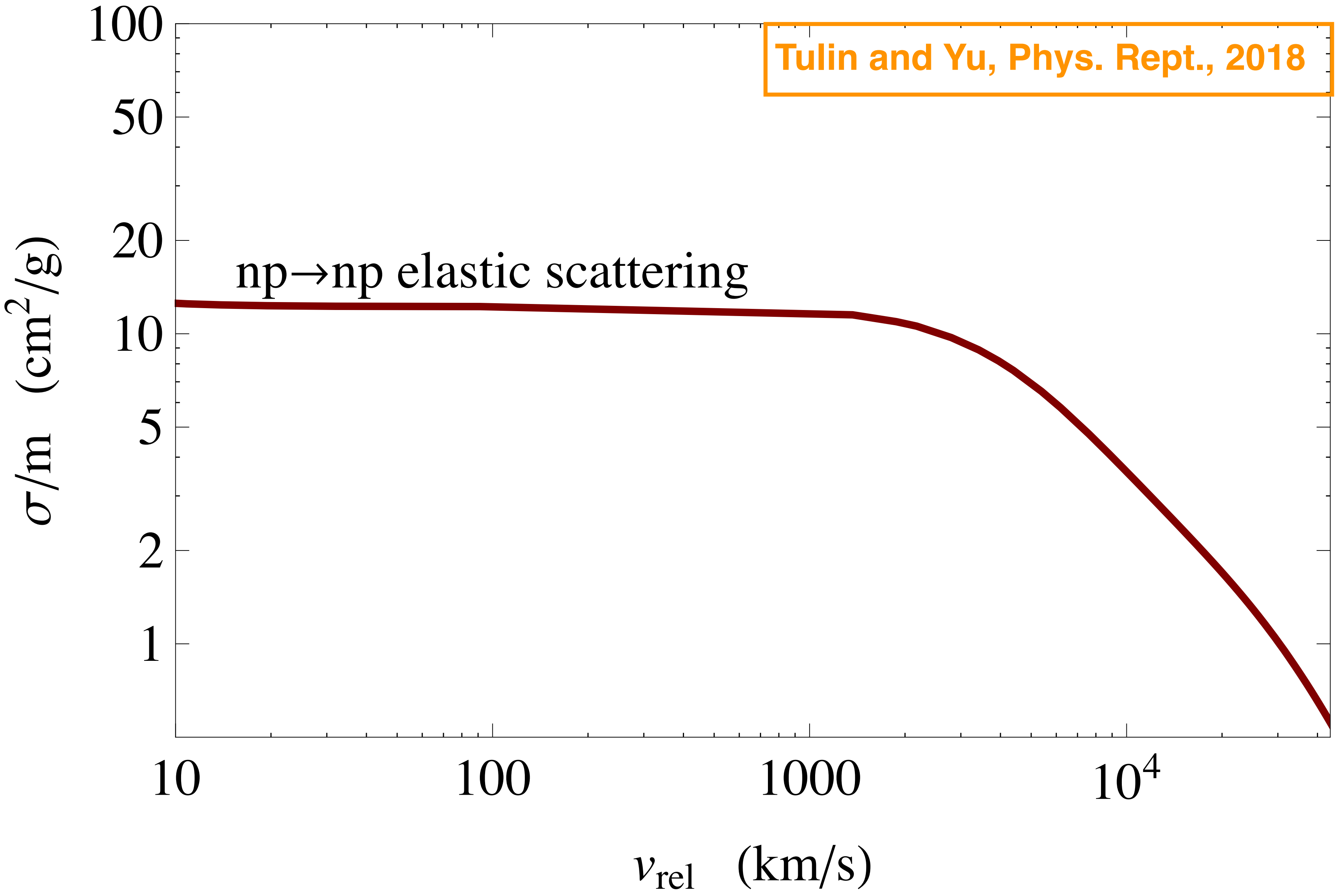
$\rightarrow \sigma/m \sim 0.1\mathrm{cm}^2/\mathrm{g}$

Kaplinghat, Tulin, and Yu, PRL, 2016

Self-interacting dark matter

SM strong dynamics: nucleon elastic-scattering cross section

- diminishing w/ increasing velocity



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 $\Lambda_{\mathrm{QCD}'}/M_* \ll 1$
- B' number asymmetry - cogenesis

Portal operator

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

$\ast$ 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

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

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' $\bar{u}'$ d' $\bar{d}'$

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

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

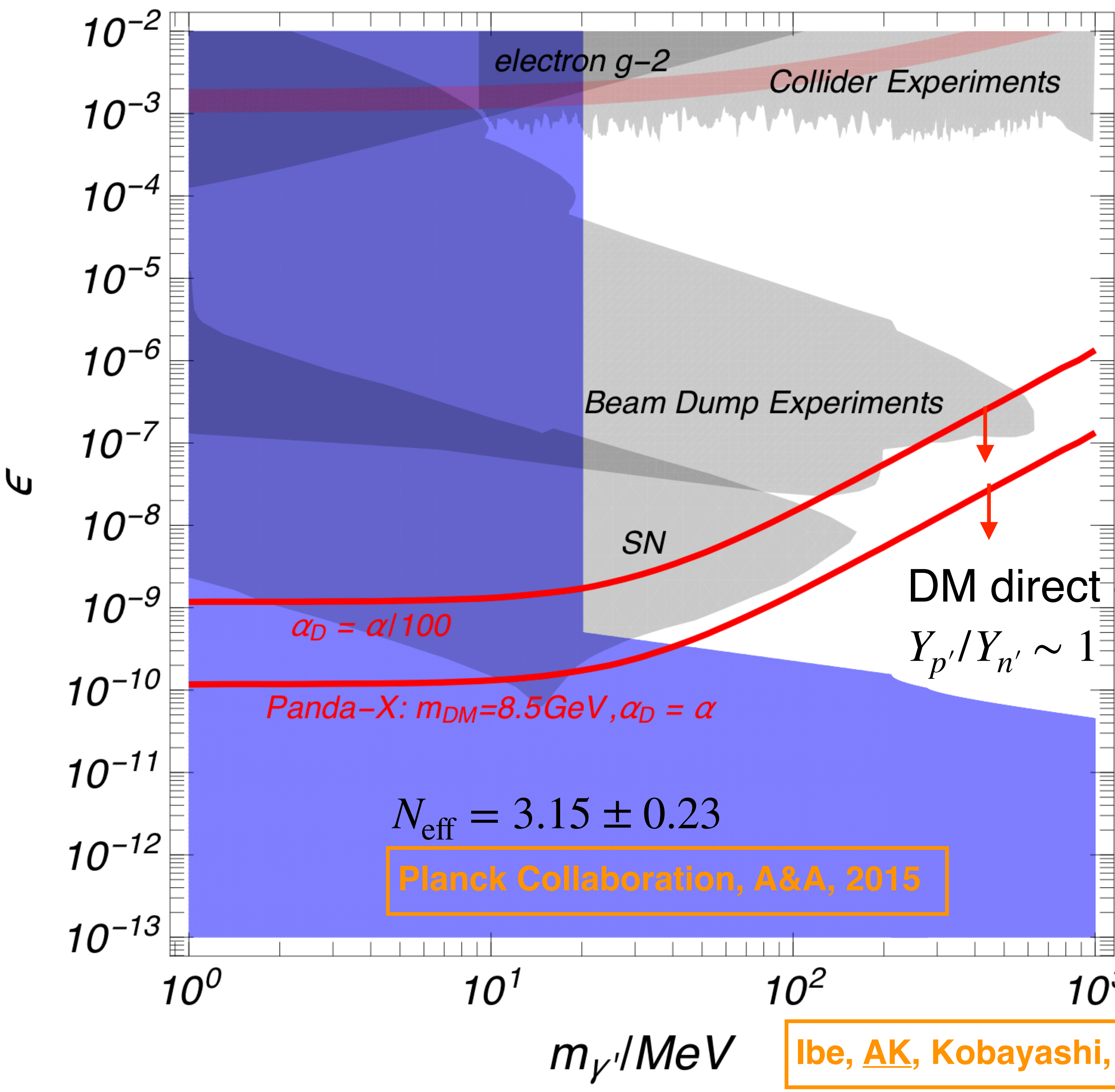
- thermal leptogenesis → $B-L$ asymmetry
- see-saw mechanism → active neutrino mass
- only $\frac{y_N}{M_{H_C}^2 M_R}\bar{u}'\bar{d}'\bar{d}'LH$ and ✕ $\frac{y_N}{M_{H_C}^2 M_R}\bar{u}\bar{d}\bar{d}LH$

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

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

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

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

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

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 $M'_S \gtrsim 10^3\,\mathrm{GeV} \left(\dfrac{M_R}{10^9\,\mathrm{GeV}} \right)^{1/2}$

Mirror grand unification

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

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

- softly broken

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

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

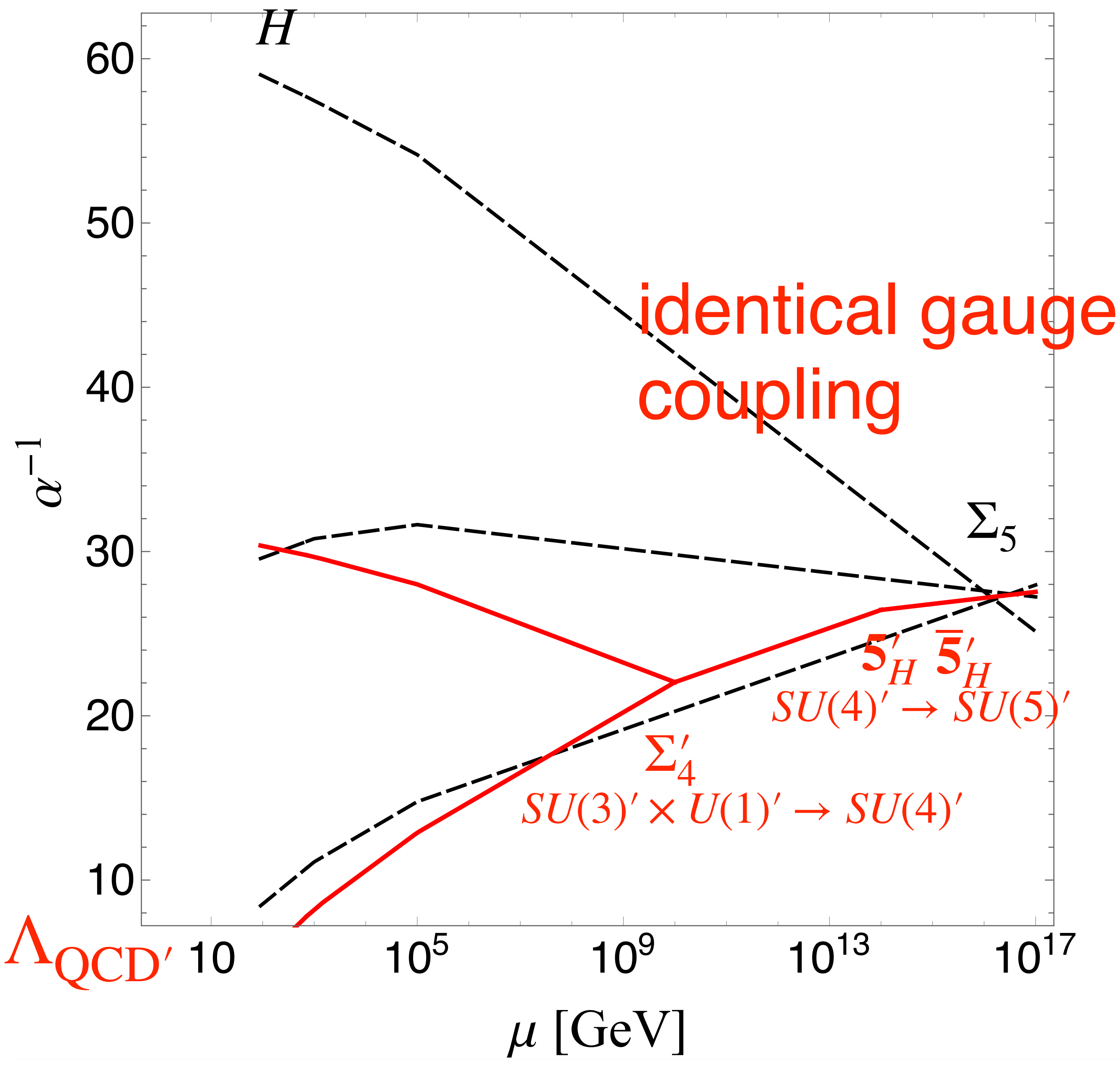
$\mathbf{10}' : (\mathbf{6}'(u', \overline{u}') + \mathbf{4}'(d', \overline{e}'))$

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

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

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

large VEV
→ vector-like theory

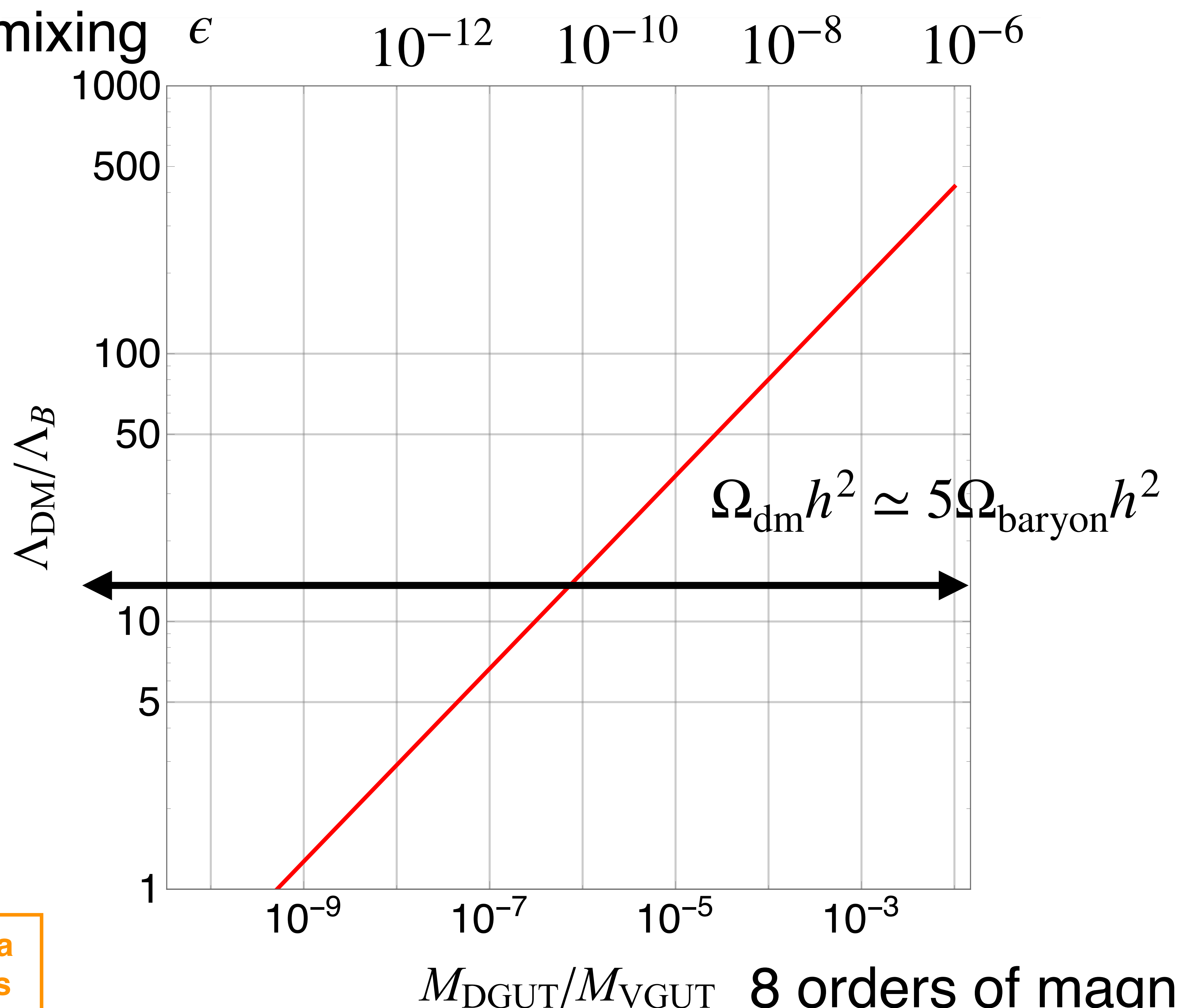


$\Lambda_{\rm QCD} \sim \Lambda_{\rm QCD'}$

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



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×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?

Thank you for your attention

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

Constraints from galaxy clusters

V_{max}~1000 km/s
↔ galaxy: V_{max}~100 km/s

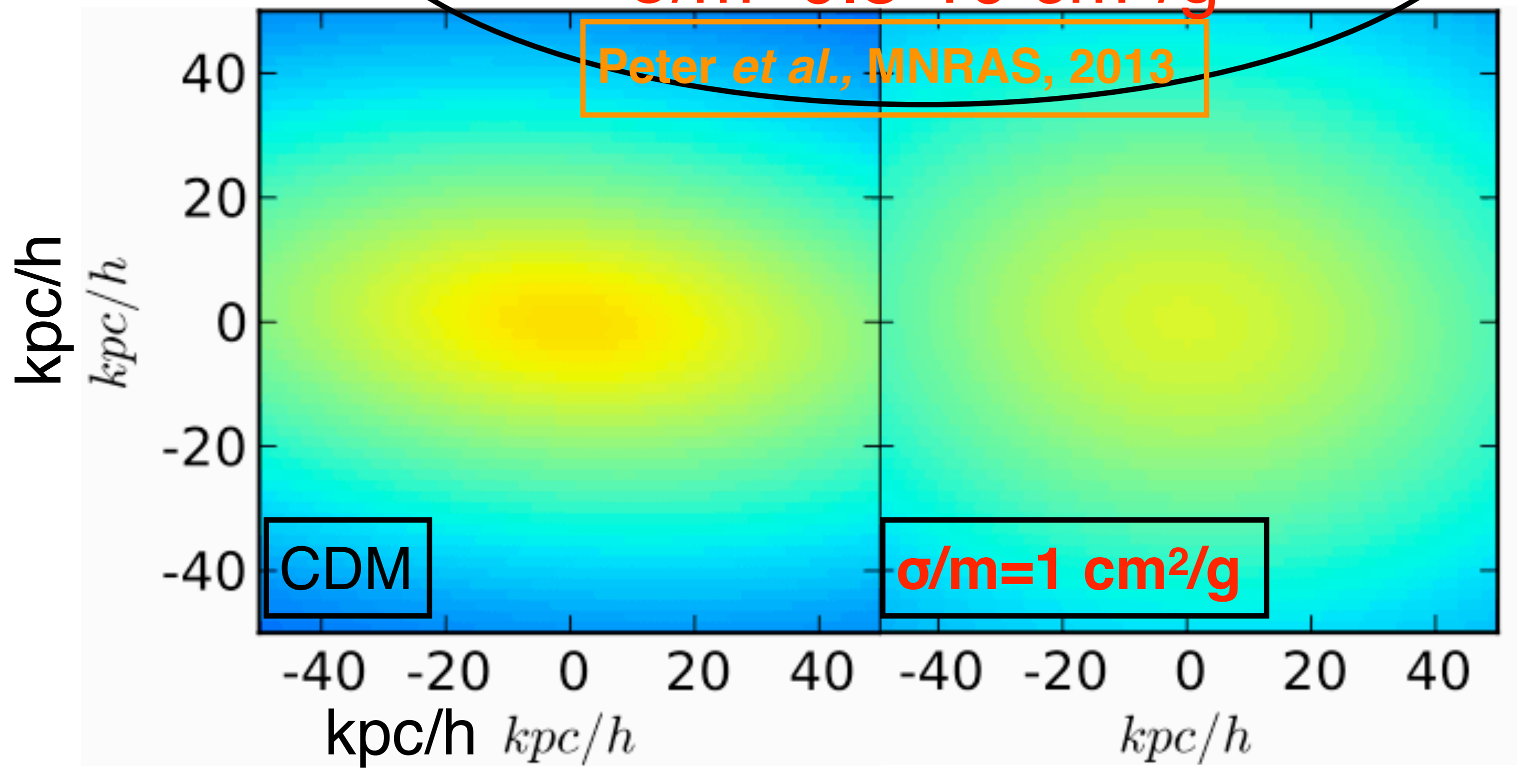
σ/m=0.5-10 cm²/g

Halo shape - ellipticity
- galaxy cluster MS 2137–23
(e=0.18@r=70 kpc)
(estimate) σ/m<0.02 cm²/g

Miralda-Escudé *et al.*, ApJ, 2002

(simulation/l.o.s. effect)
σ/m<1 cm²/g

Peter *et al.*, MNRAS, 2013

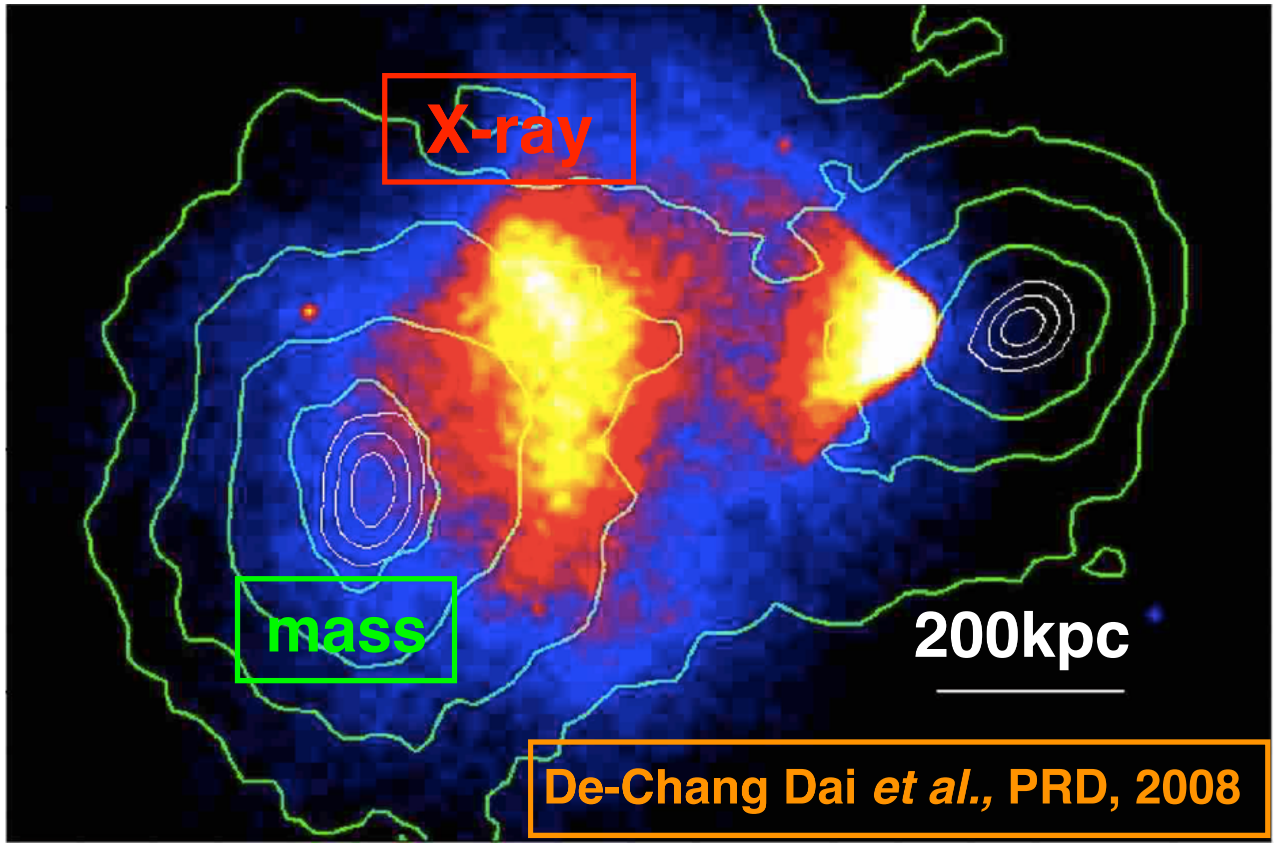


Bullet cluster - transparency
- 1E0657-558
(offset) σ/m<1.25 cm²/g
(massloss) σ/m<0.7 cm²/g

Randall *et al.*, ApJ, 2008

- an ensemble (72)
(offset) σ/m<0.47 cm²/g

Harvey *et al.*, Science, 2015

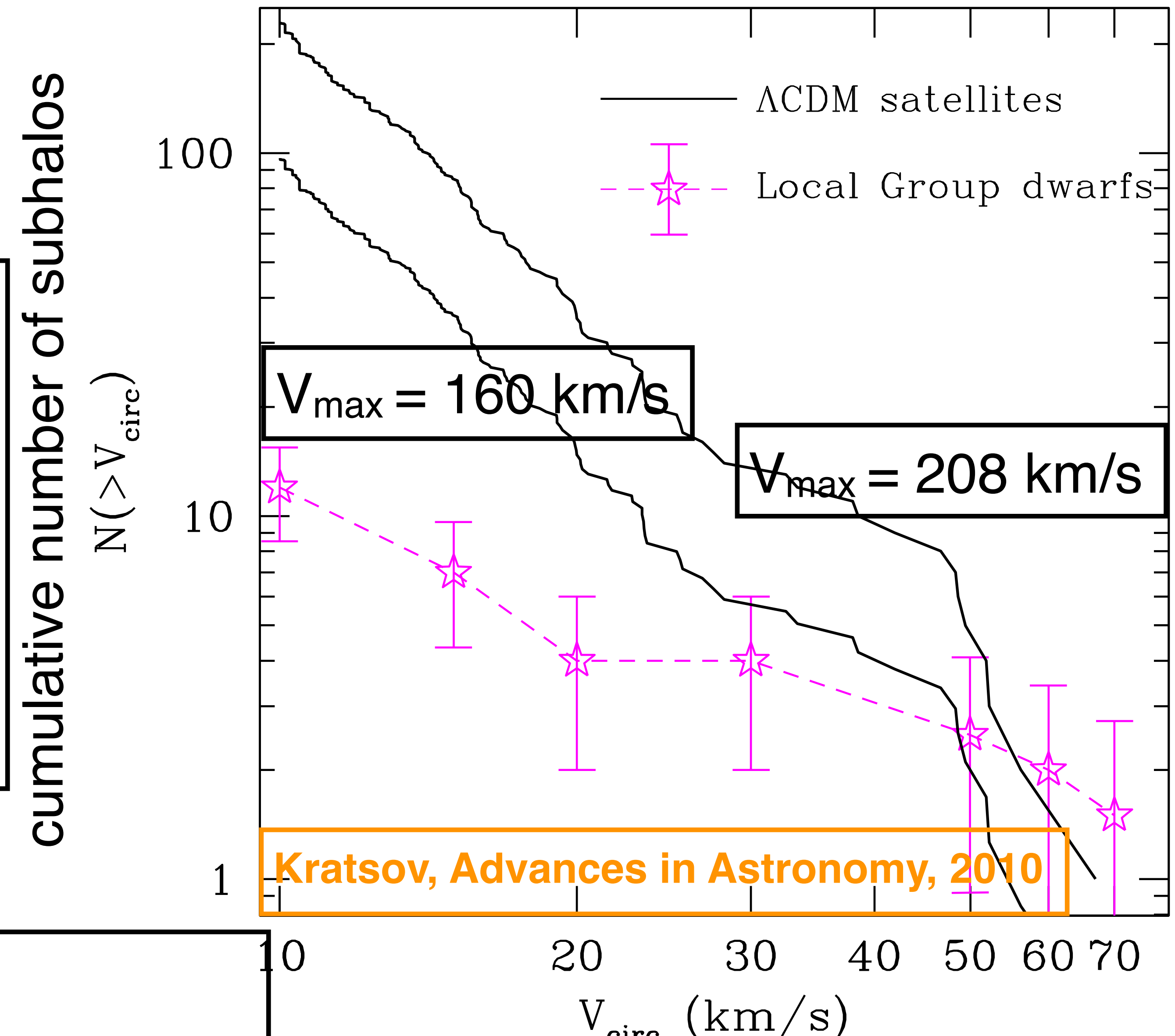


Small scale crisis I

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

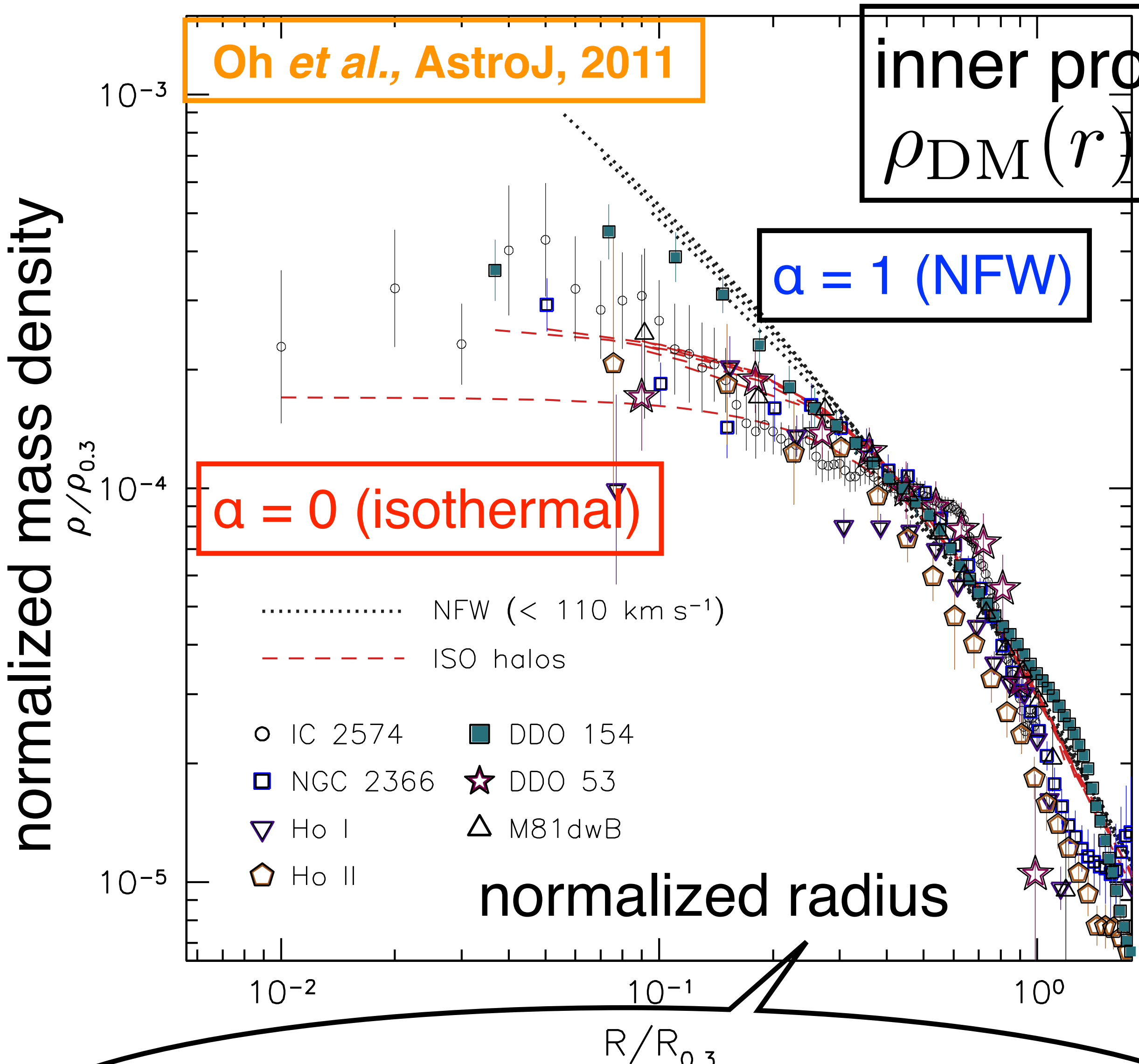
$$V^2_{\rm circ}(r) = \frac{GM(<r)}{r} \qquad V_{\rm max} = \max_r \{V_{\rm circ}(r)\}$$

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:

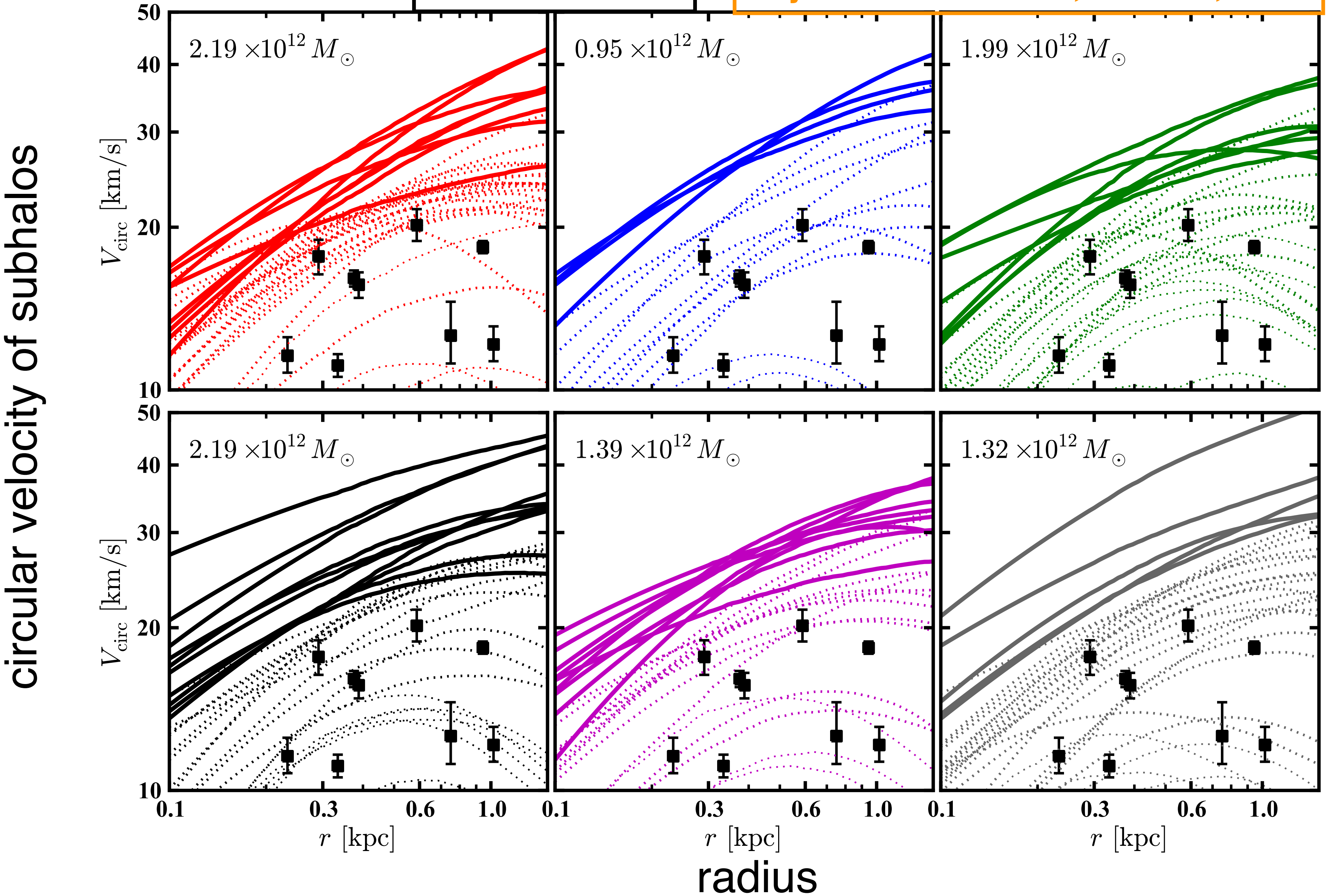
$$\rho_{\rm DM}(r) = \rho_{\rm DM}^0 \begin{cases} 1 & (r \ll r_0) \\ (r_0/r)^2 & (r \gg r_0) \end{cases}$$

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

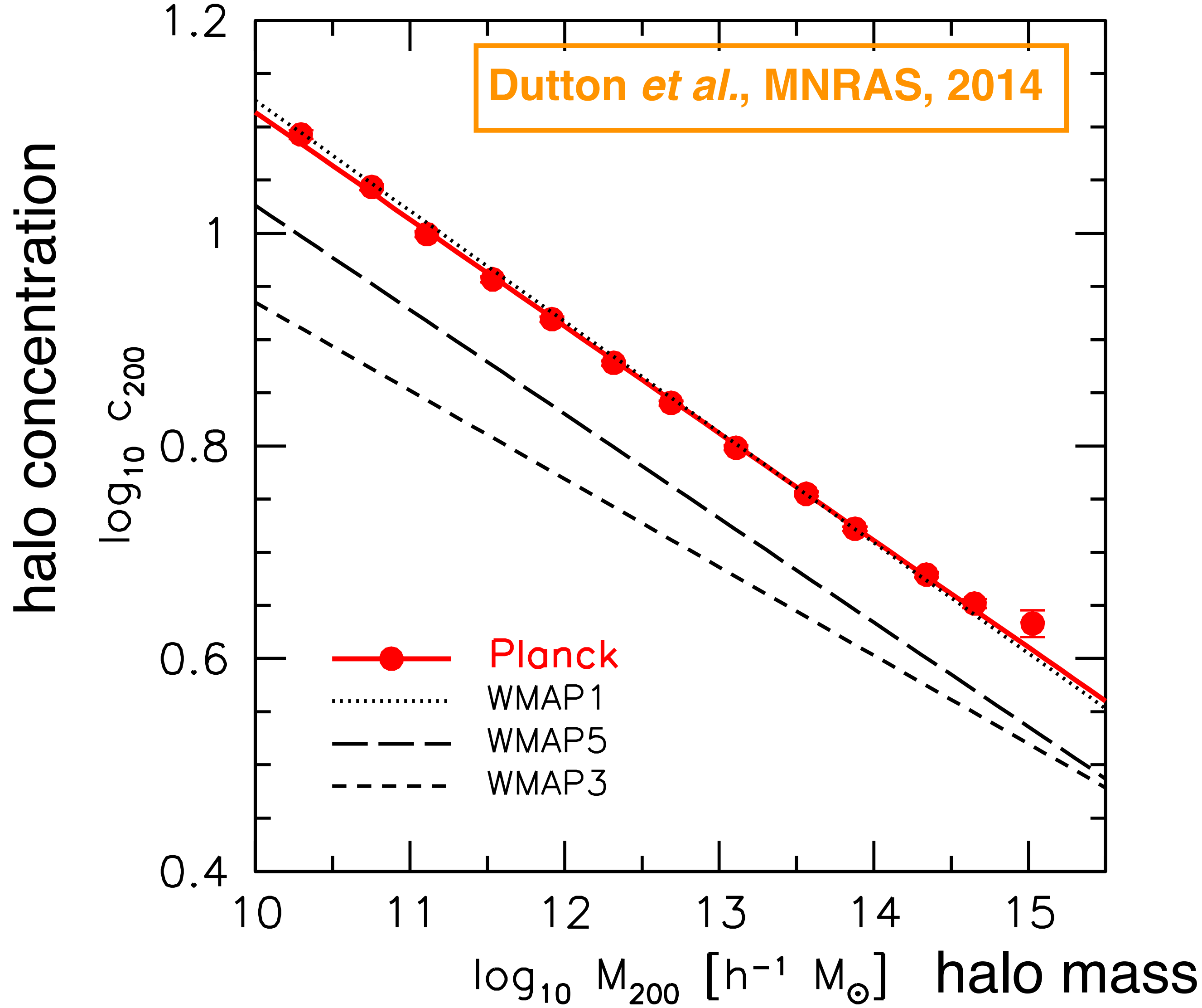
Why is a simulated rotation curve (almost) **DEFINITE** for a given V_{max}?
Two parameters for the NFW profile

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

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

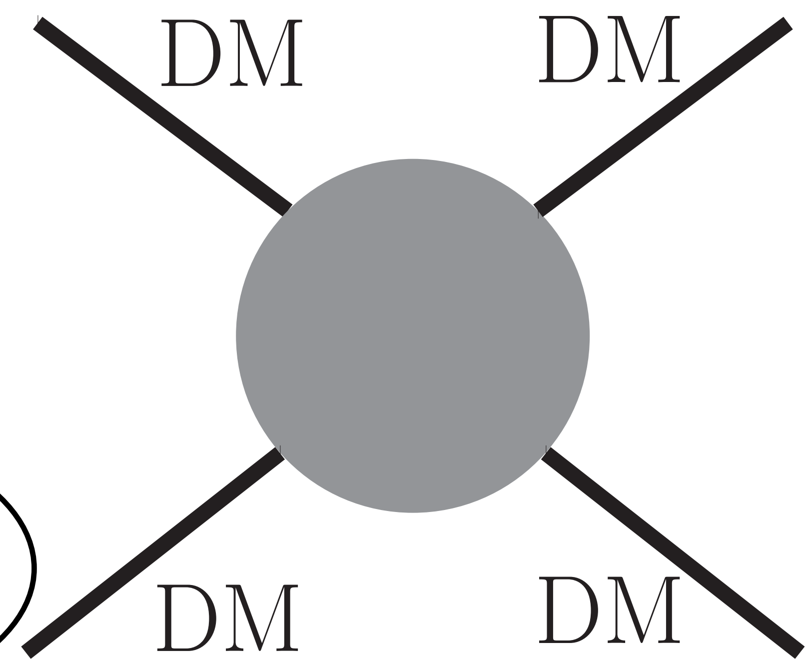


$$c_{200} = r_{200}/r_s$$

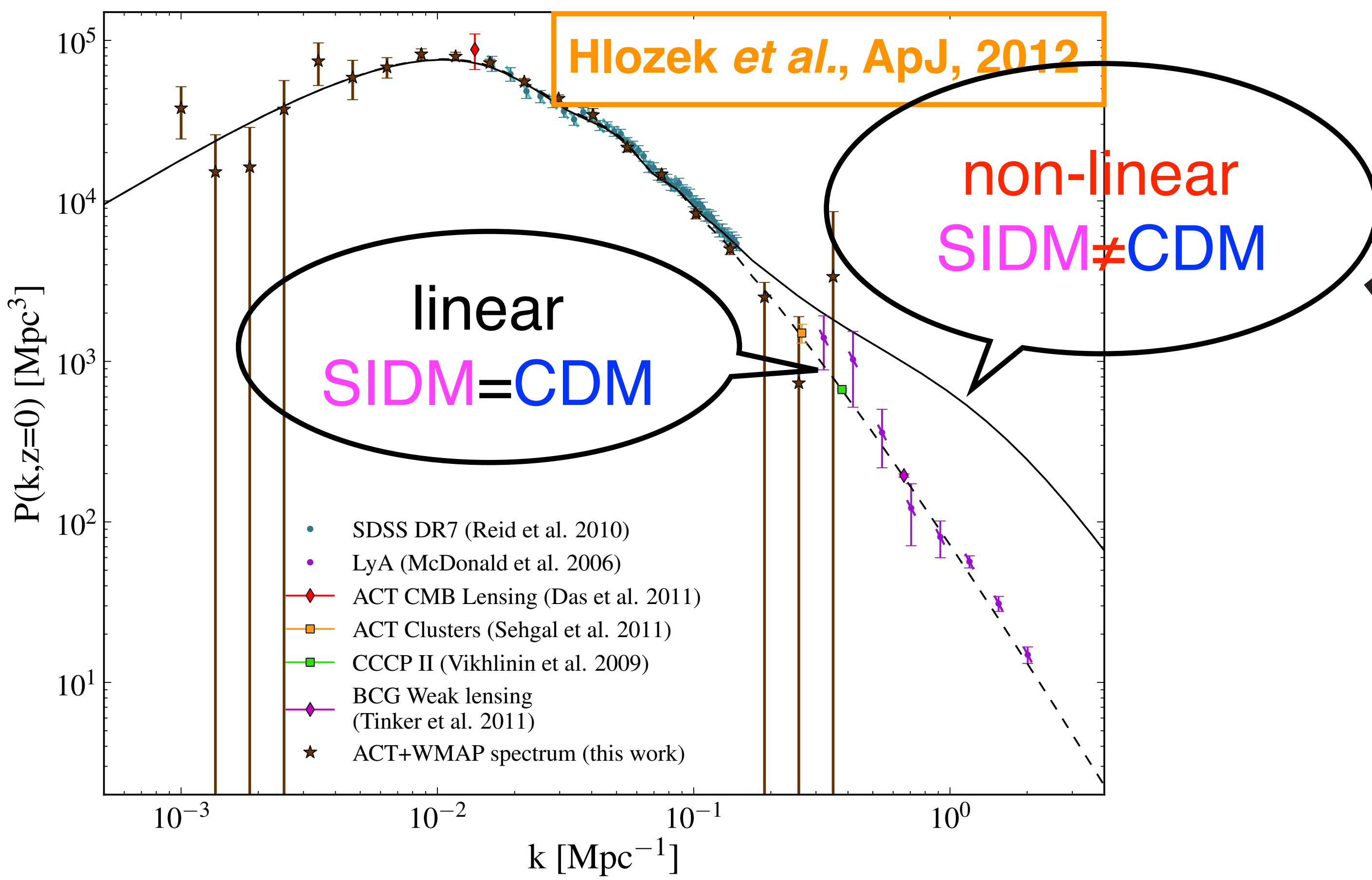
$$M_{200}(<r_{200}) = \frac{4\pi}{3}\bar{\rho}_{\rm M} r_{200}^3$$

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

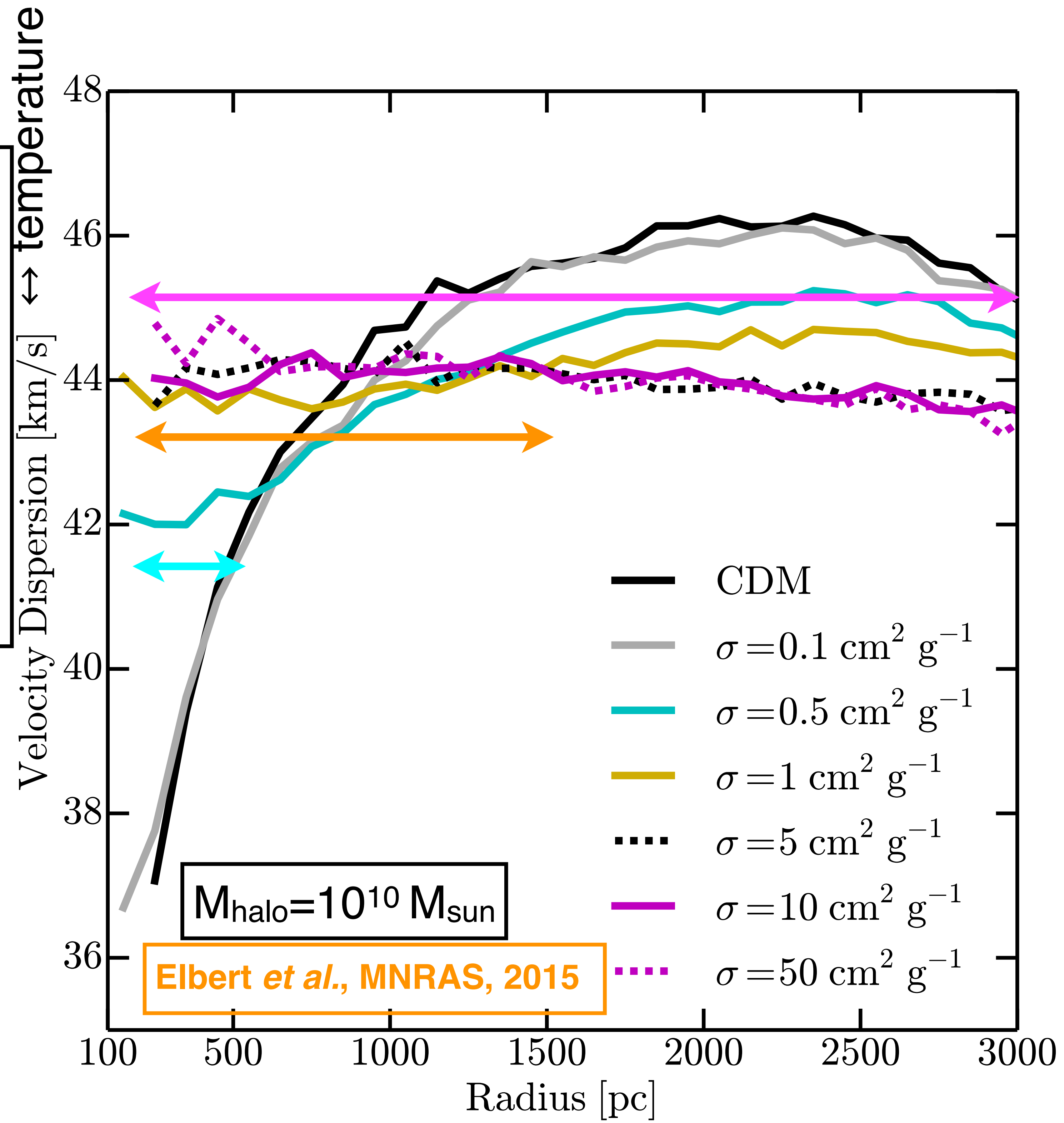
SIDM-only simulation

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

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

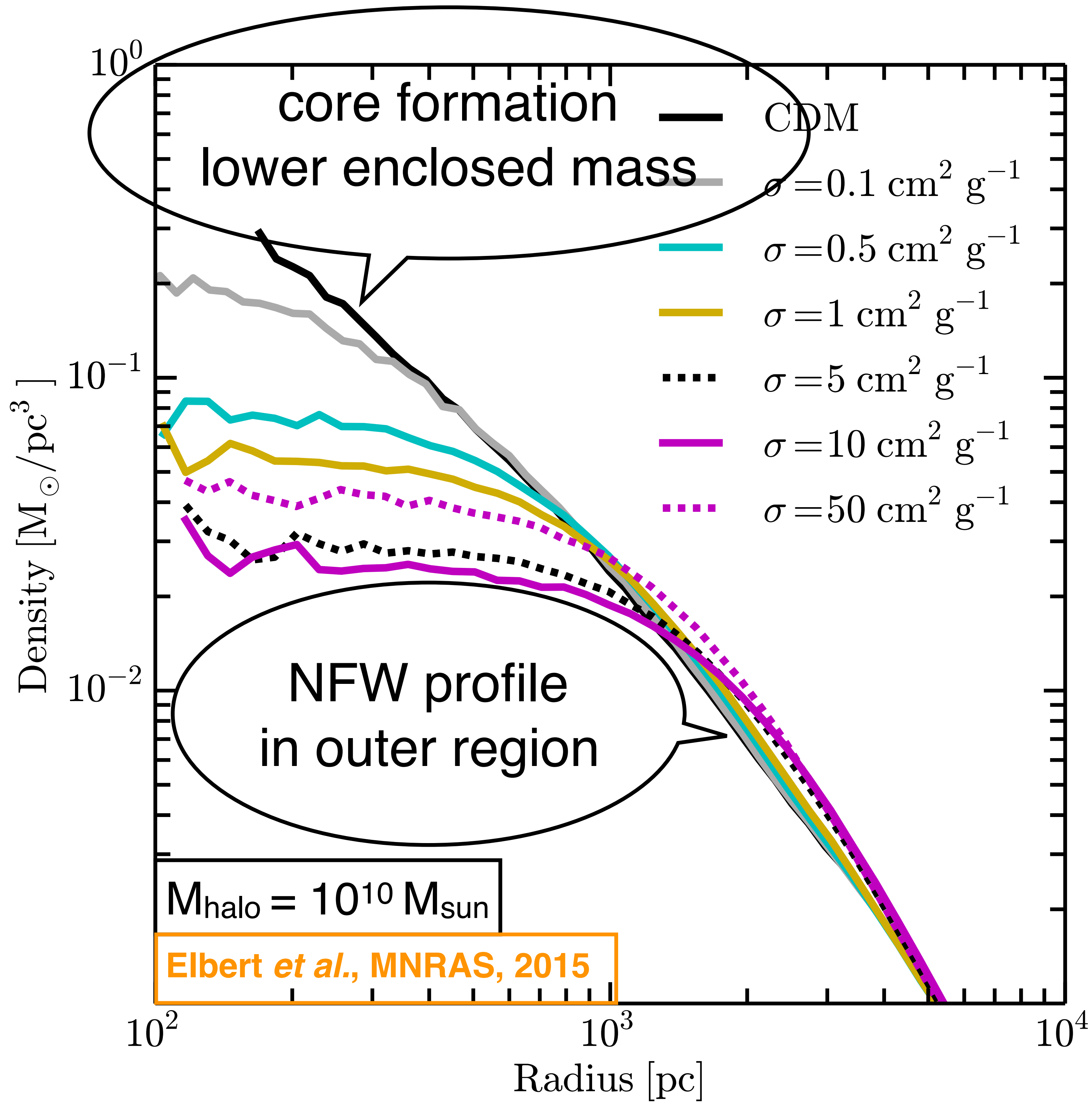


SIDM halo - mass density

SIDM-only simulation

As σ/m increases,
central density decreases

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

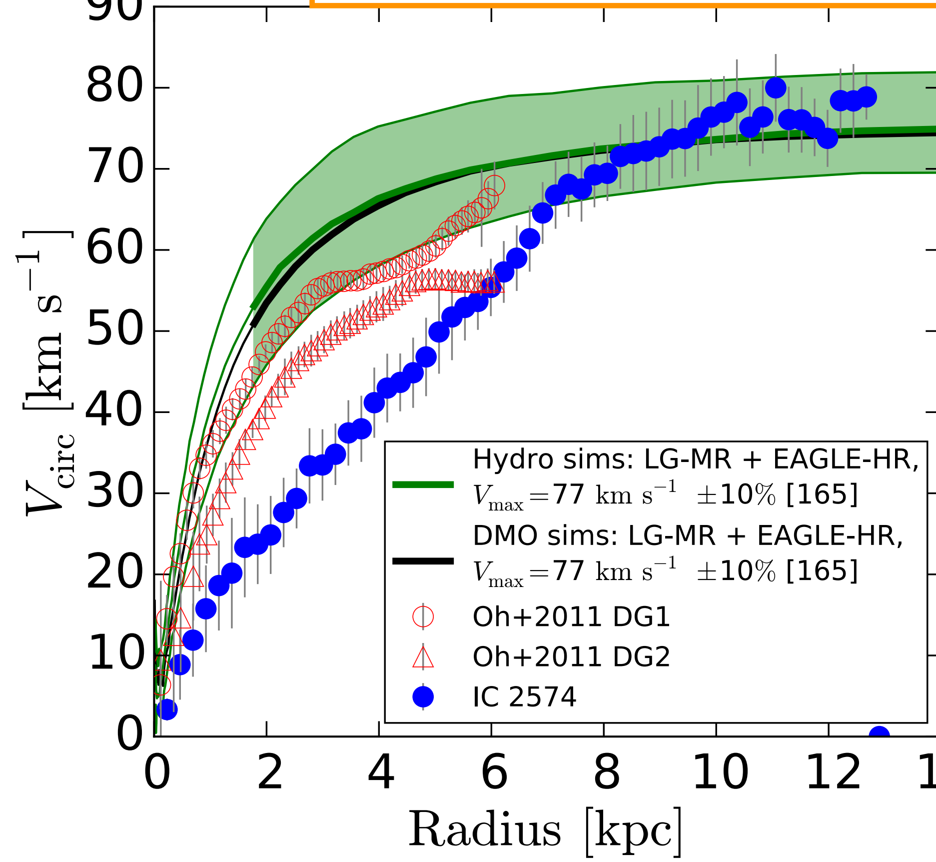


σ/m = 0.5-5 cm²/g may solve the inner mass deficit problem

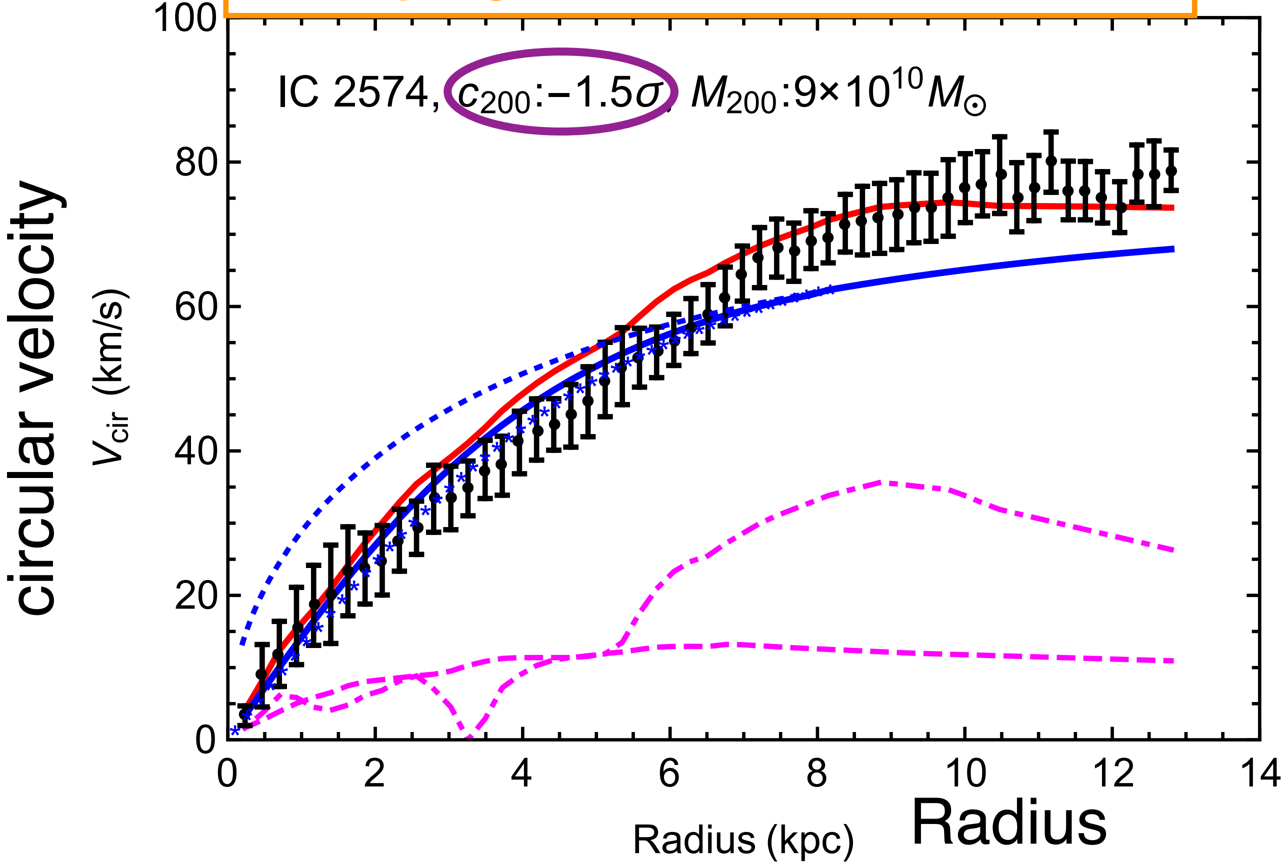
Intrinsic scatter

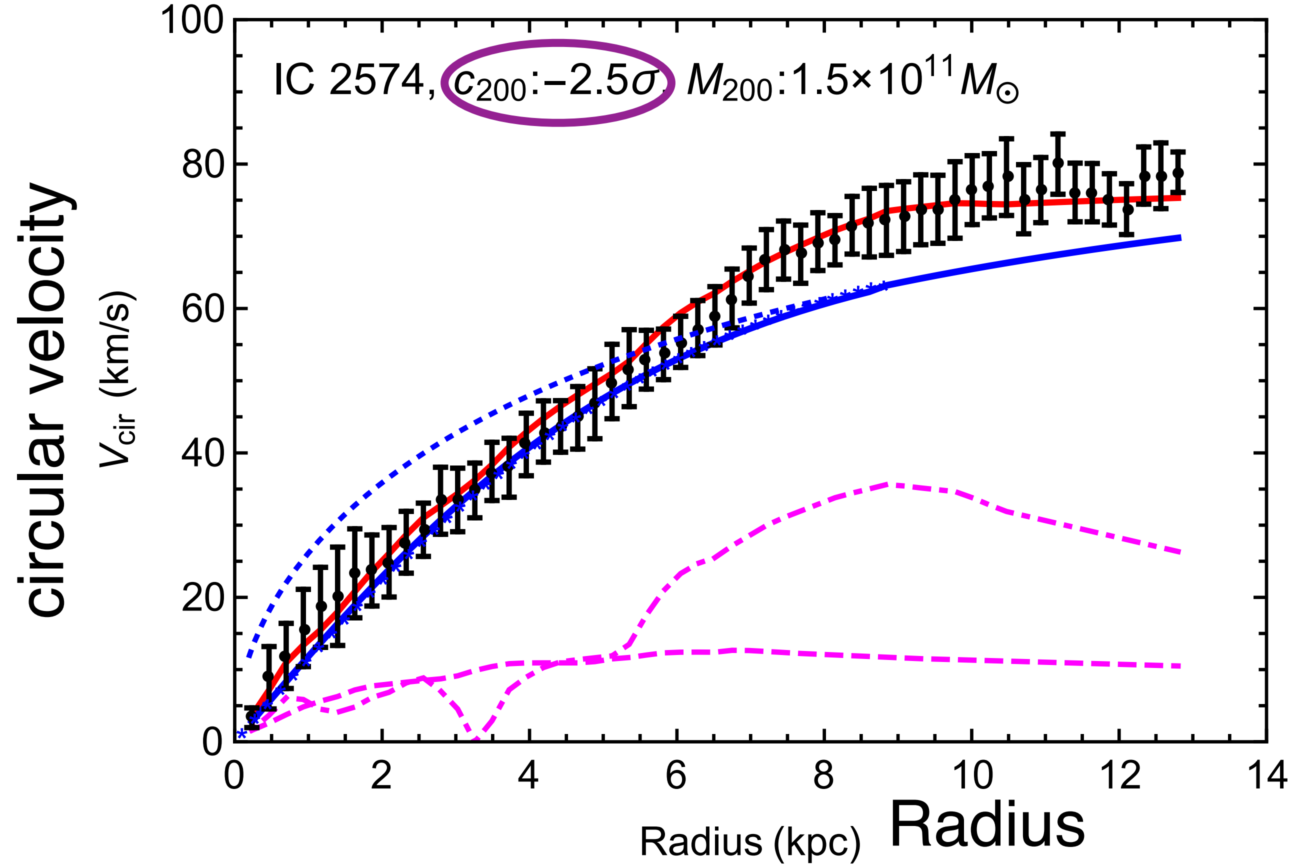
Intrinsic diversity of DM halos should be taken into account to explain the observed diversity

Oman *et al.*, MNRAS, 2015



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

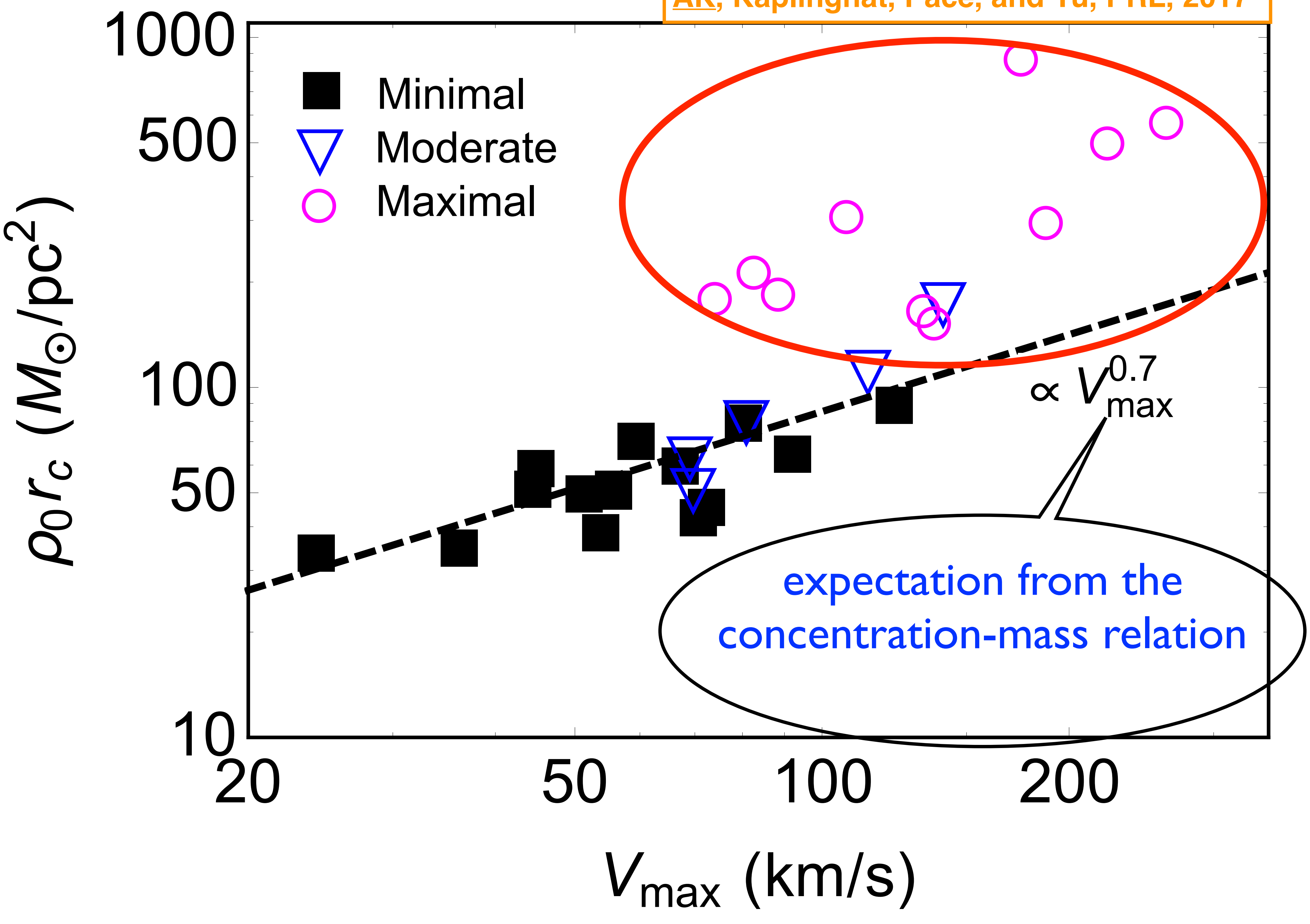




More samples

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

$$\mathscr{L}_{\text{mass}} = m_{u'} u'\bar{u}' + m_{d'} d'\bar{d}'$$

→ dark pions

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

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

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

∗ 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	$\mathbf{3}$	$-1/3$	$-2/3$

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

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

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

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

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

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

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

Entropy transfer

$U(1)'$ breaking scalar $H^{+'}$ $$\mathcal{L}_{A'} = \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{m_{\gamma'}}{2} A'_\mu A'^\mu$$

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

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

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

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

- impacting DM direct detection

Krnjaic and Sigurdson, PLB. 2015…

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

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