Dark matter self-interactions: Galactic rotation curves and composite asymmetric dark matter

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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, arXiv: 1805.06876

Oct. 5, 2018 @ ECT*

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

Particle dark matter

Why is a dark matter particle long-lived?

- new $\mathbb{Z}_2$ symmetry
  - e.g., matter parity: $U(1)_{B-L} \to (-1)^{3(B-L)}$
  - thermal freeze-out → $\Omega_{\rm dm} h^2 \simeq 0.12$

→ WIMP

- 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 $Y_{\Delta B'} \sim Y_{\Delta B}$

$$m_{N'} \sim \Lambda_{\rm QCD'} = \mathcal{O}(1)\,{\rm GeV} \to \Omega_{\rm dm} h^2 \simeq 5\Omega_{\rm baryon} h^2 \simeq 0.12$$

→ composite asymmetric dark matter

Asymmetric dark matter

Portal operator

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

✳ if no particle charged under both gauge groups

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

→ at high energy (temperature) $U(1)_{B-L+\alpha B'} \subset U(1)_{B-L} \times U(1)_{B'}$

Thermal history outline

SM | dark

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

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

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

Thermal history continued

SM

sphaleron process decoupled

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

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

QCD phase transition

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

pair annihilation of nucleons into pions

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

dark

QCD' phase transition

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

pair annihilation of nucleon's

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

Composite DM naturally features efficient annihilation of the symmetric component

$(\sigma v) \sim 4\pi / \Lambda^2_{\mathrm{QCD}'}$

What I will address

part 1

Origin of the portal operator?

- 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

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

Asymmetry generation?

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

Fukugita and Yanagida, PLB, 1986

Where dark sector entropy is gone?

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

part 2

Implications for structure formation?

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

Part 1: Simple model

Model setup: QCD×QED-like confinement 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

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

→ 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 $T \sim M_R > 10^9\,\mathrm{GeV}$
- see-saw mechanism → active neutrino mass $LH\overline{N} \xrightarrow{\overline{N}} \frac{1}{M_R} LHLH$
- generation of the portal operator

Scalar quark $\widetilde{d}'$ w/ mass M_C

$$\widetilde{d}'^{\dagger}\overline{u}'\overline{d}' \qquad \widetilde{d}'\overline{d}'\overline{N}$$

$$\xrightarrow{\widetilde{d}'} \frac{1}{M_C^2}\overline{u}'\overline{d}'\overline{d}'\overline{N} \qquad LH\overline{N}$$

$$\xrightarrow{\overline{N}} \frac{1}{M_C^2 M_R}\overline{u}'\overline{d}'\overline{d}'LH$$

	$SU(3)_D$	$U(1)_D$	$U(1)_{B-L+B'}$
$\widetilde{d}'$	**3**	$-1/3$	$1/3$

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

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

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

✳ decoupling after leptogenesis $M_C \sim M_R$

Entropy transfer

$U(1)_D$ breaking scalar $\widetilde{e}'$

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

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

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

- 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 $\Gamma_{\gamma' \to e\bar{e}}$

- 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: $\frac{1}{M_C^2 M_R} \bar{u}' \bar{d}' \bar{d}' L H \rightarrow m_{\rm DM} \simeq 8.5\,{\rm GeV}$

Weinberg, "Cosmology"

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

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

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

for reference

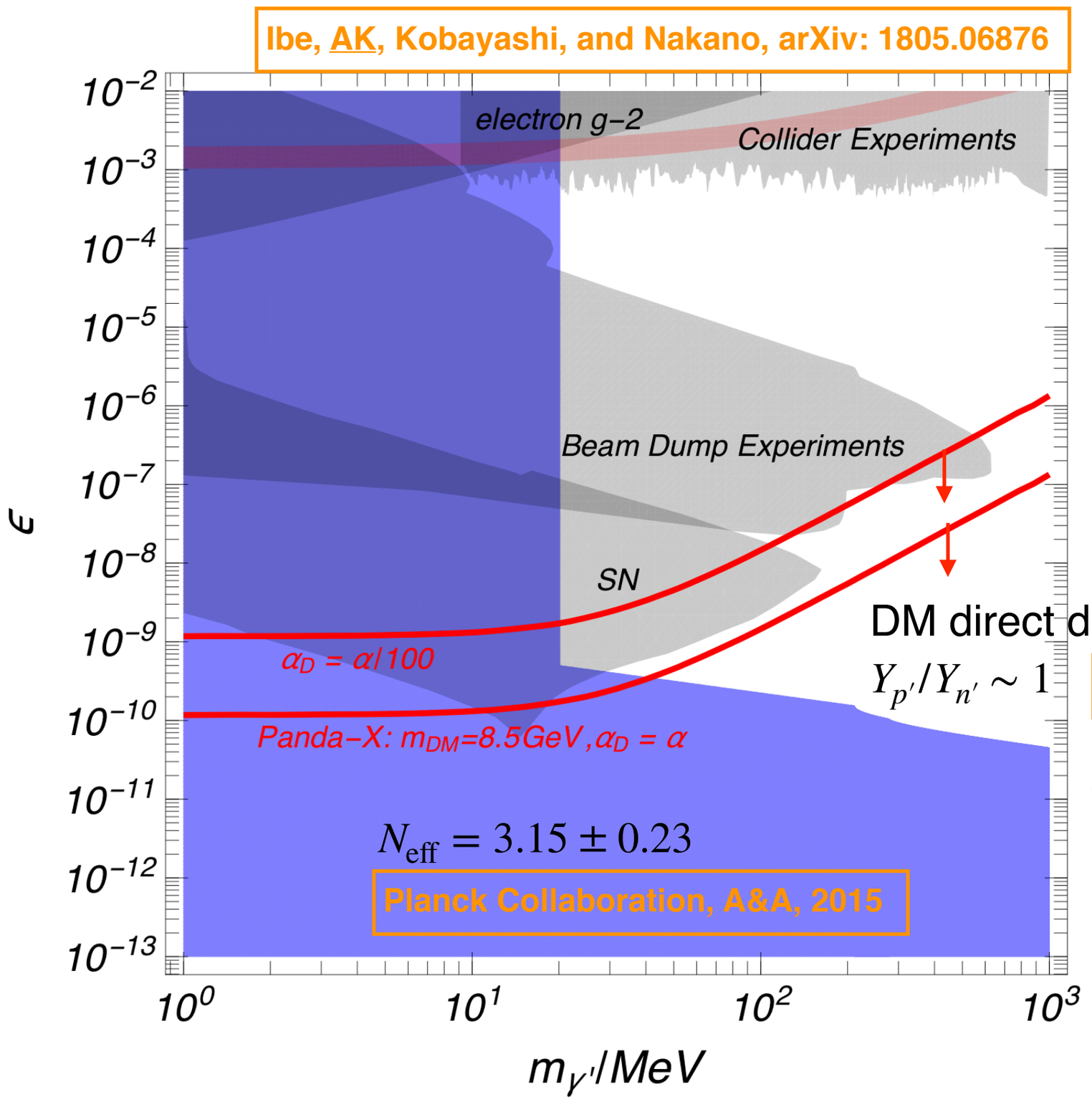
$m_n - m_p \simeq 1.2\,{\rm MeV}$ $\quad m_\pi \simeq 140\,{\rm MeV}$

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

Krnjaic and Sigurdson, PLB. 2015…

- impacting DM direct detection

Dark photon parameter plot



DM direct detection

$Y_{p'}/Y_{n'} \sim 1$

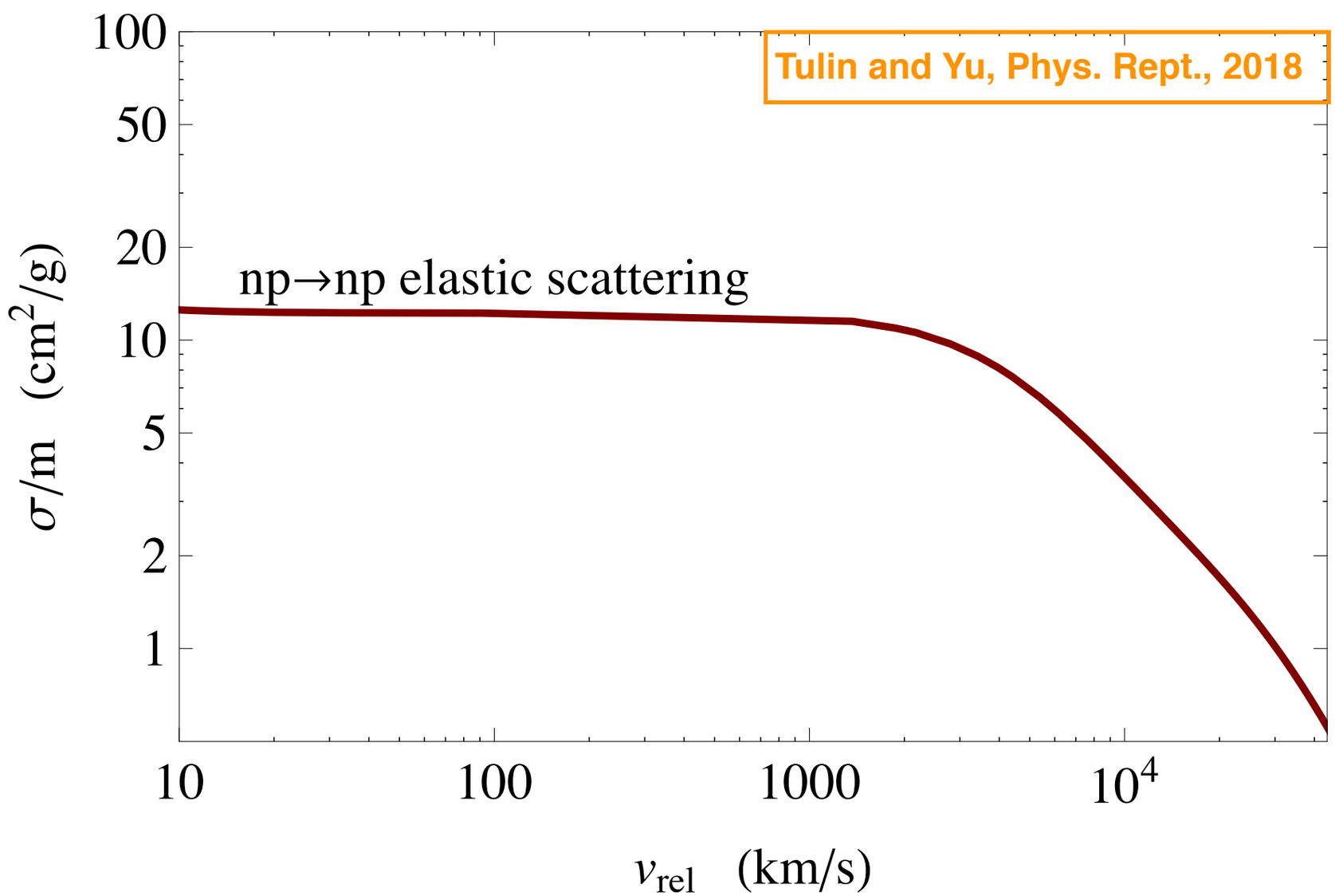
Del Nobile, Kaplinghat, and Yu, JCAP, 2015

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

Part 2: Self-interacting dark matter

SM nucleon elastic scattering cross section

- diminishing w/ increasing velocity

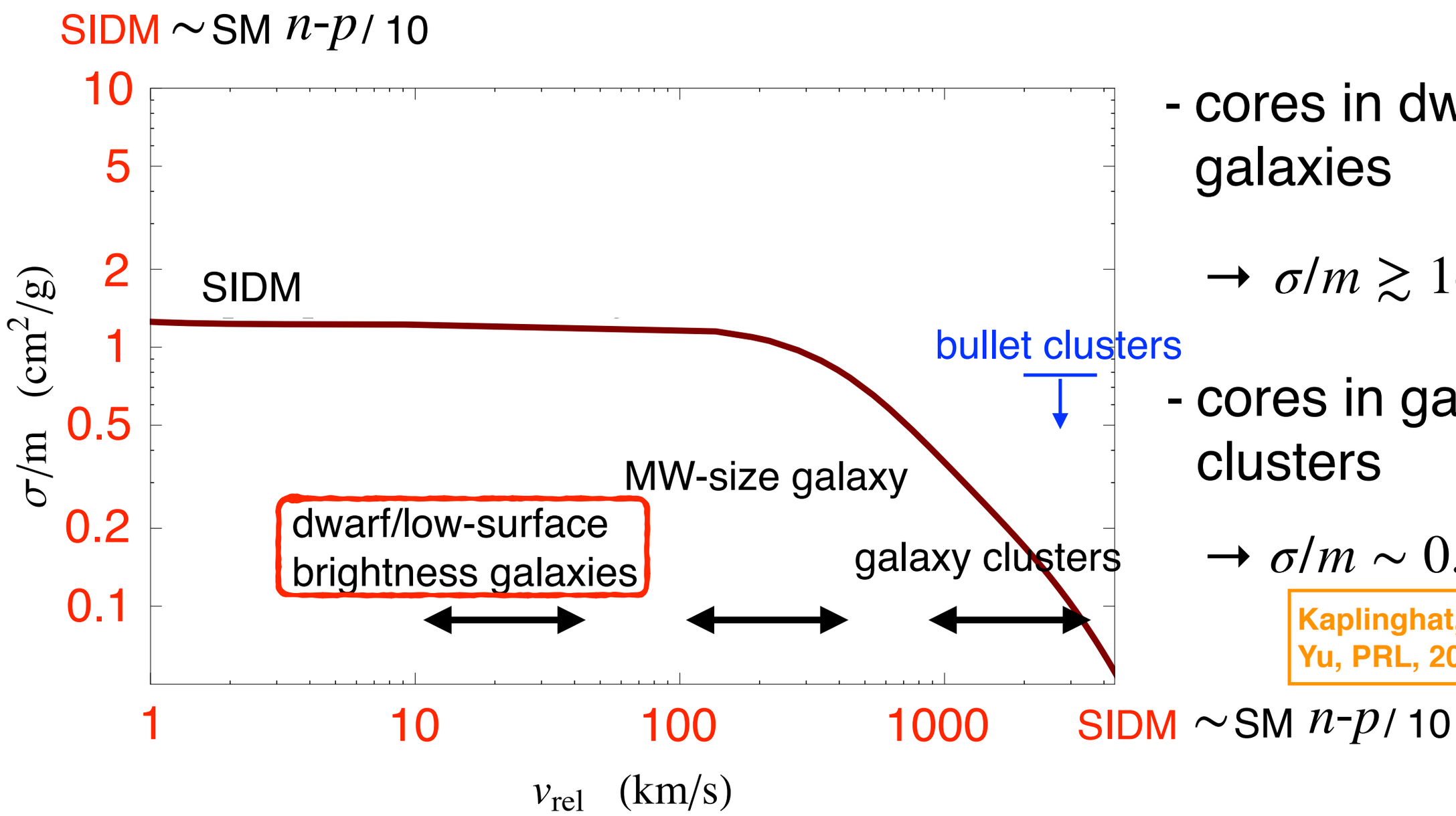


$\Lambda_{\mathrm{QCD}'} = \mathcal{O}(1)\,\mathrm{GeV}$

How it changes with a quark mass and the dynamical scale?

Self-interacting dark matter

DM self-scattering cross section indicated by small-scale puzzles



- cores in dwarf galaxies

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

- cores in galaxy clusters

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

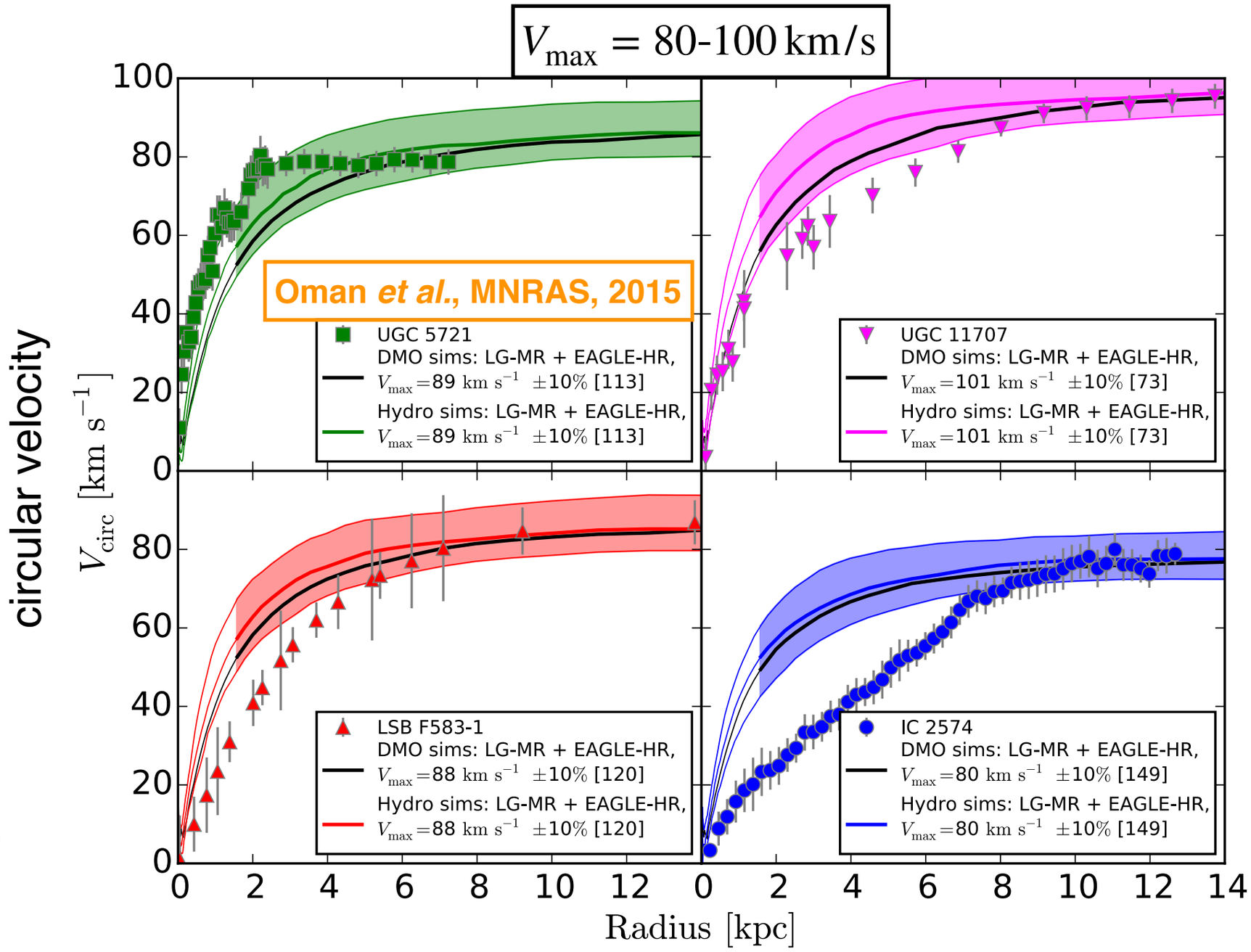
Kaplinghat, Tulin, and Yu, PRL, 2016

Diversity of inner rotation curves

Prediction: inner circular velocity is almost uniquely determined by outer circular velocity

↔ observations

show diversity



✳ unique prediction is related with the concentration-mass relation

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

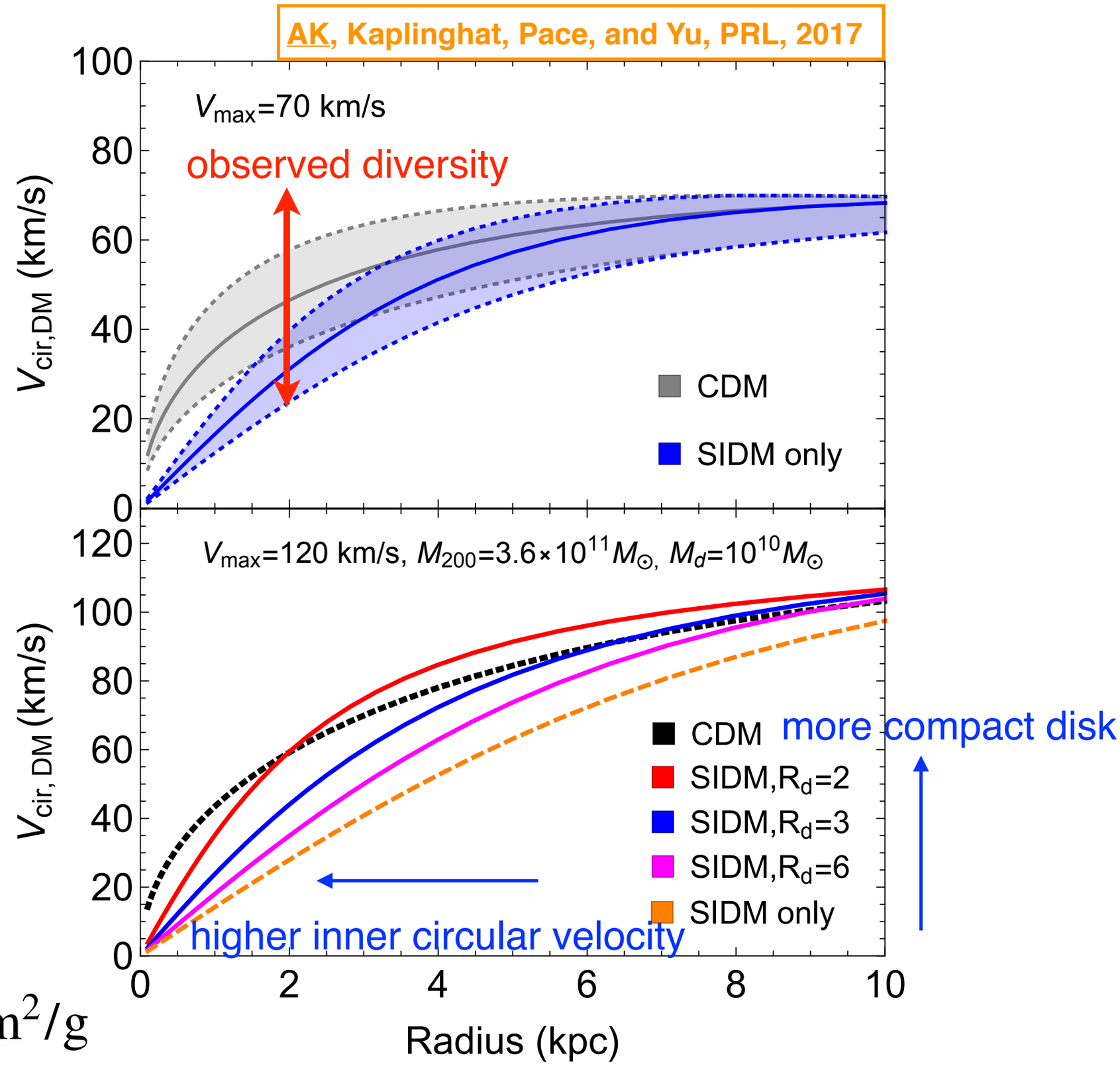
→ SIDM particles, redistributed according to formed baryonic objects, can show a diversity

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

Demonstration with stellar disks

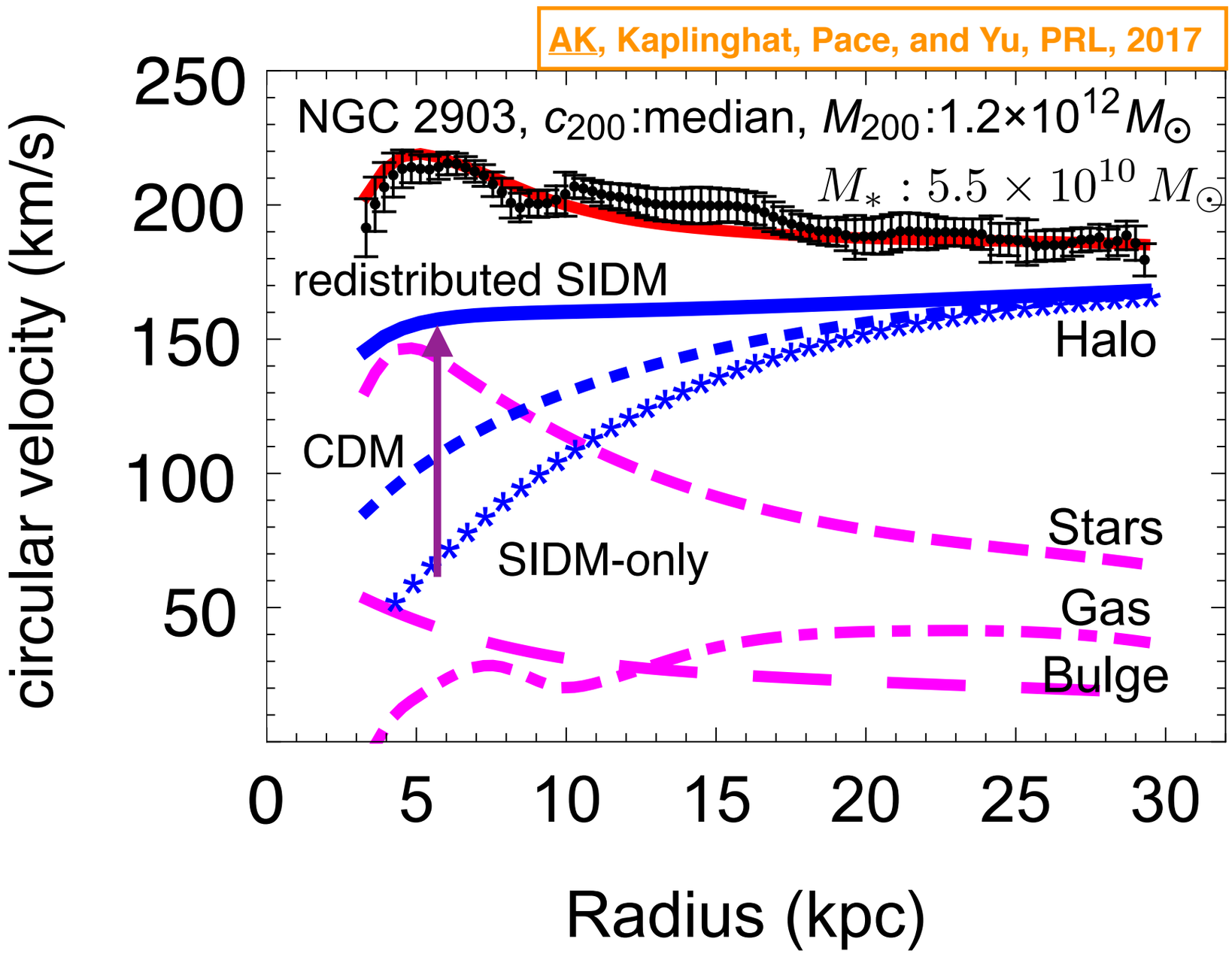
- observed diversity exceeds intrinsic diversity of DM halos

- 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



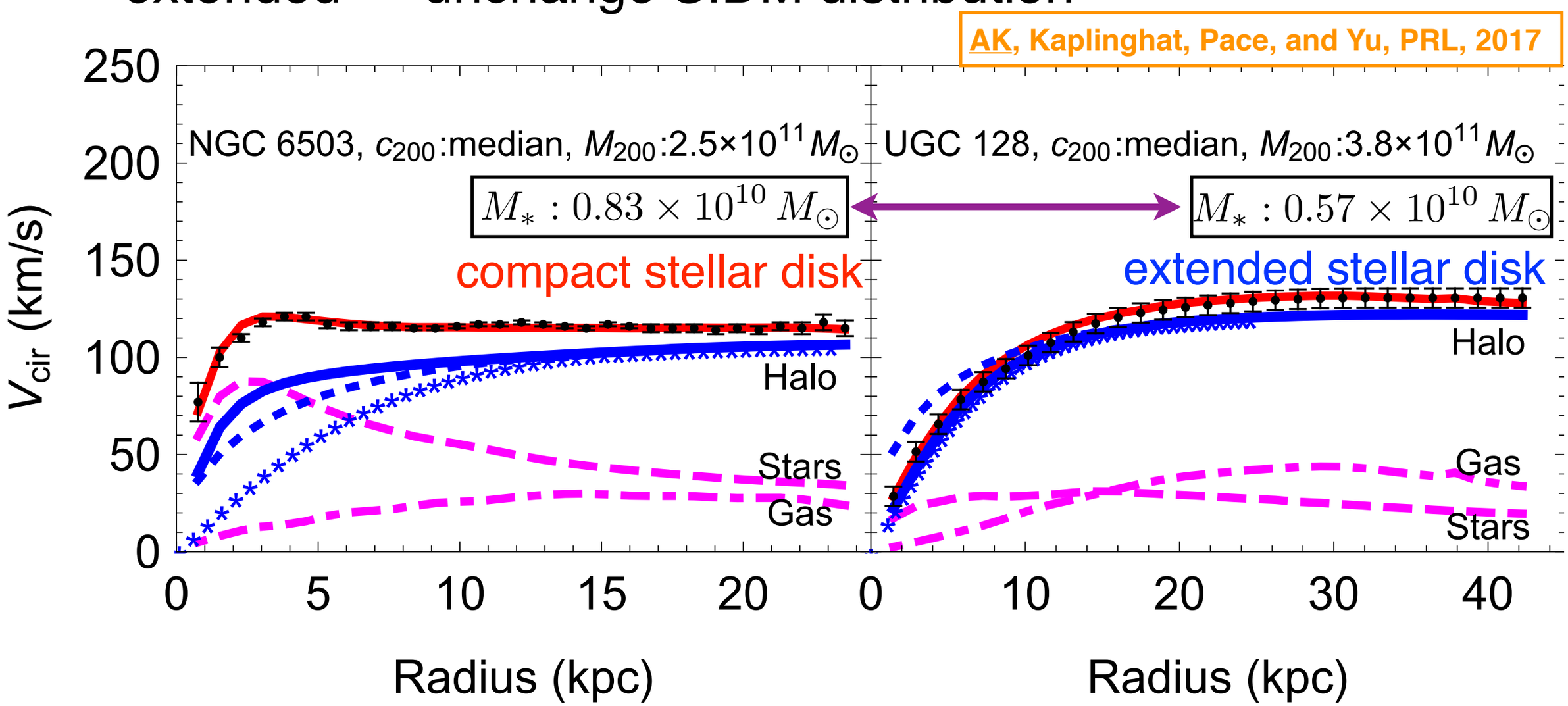
- Observed stellar disk makes SIDM inner circular velocity ~ 3 times higher

→ reproducing flat circular velocity at 10-20 kpc

Diversity in stellar distribution

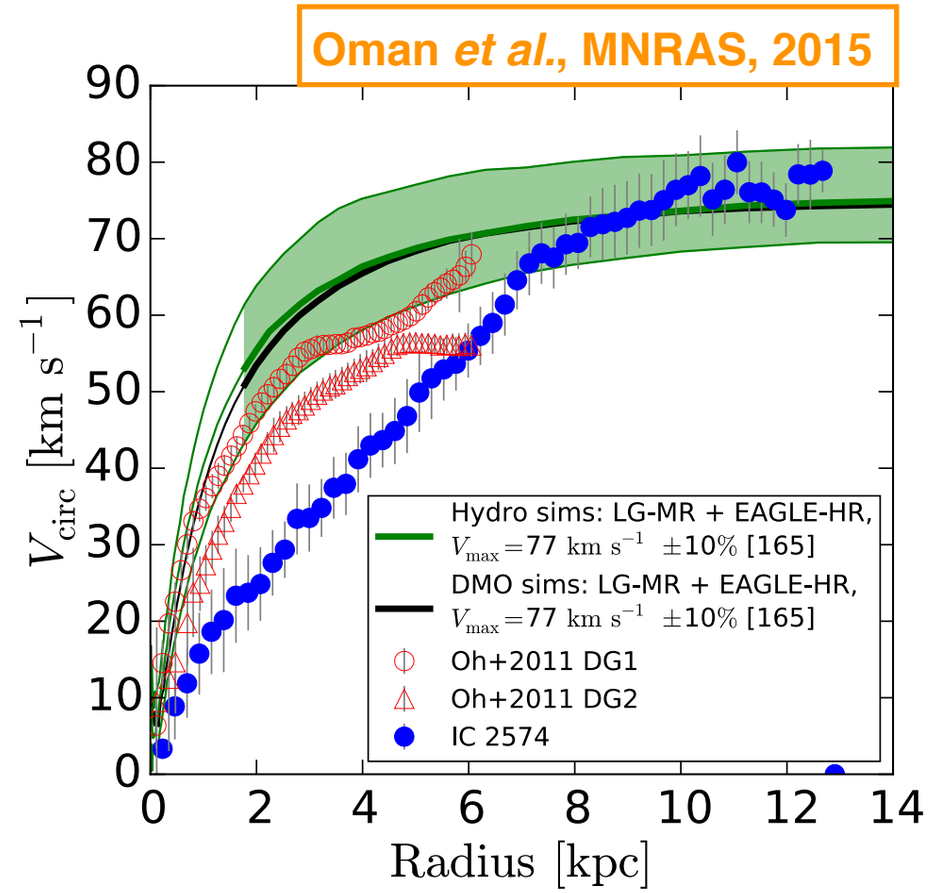
Similar outer circular velocity and stellar mass,
but different stellar distribution

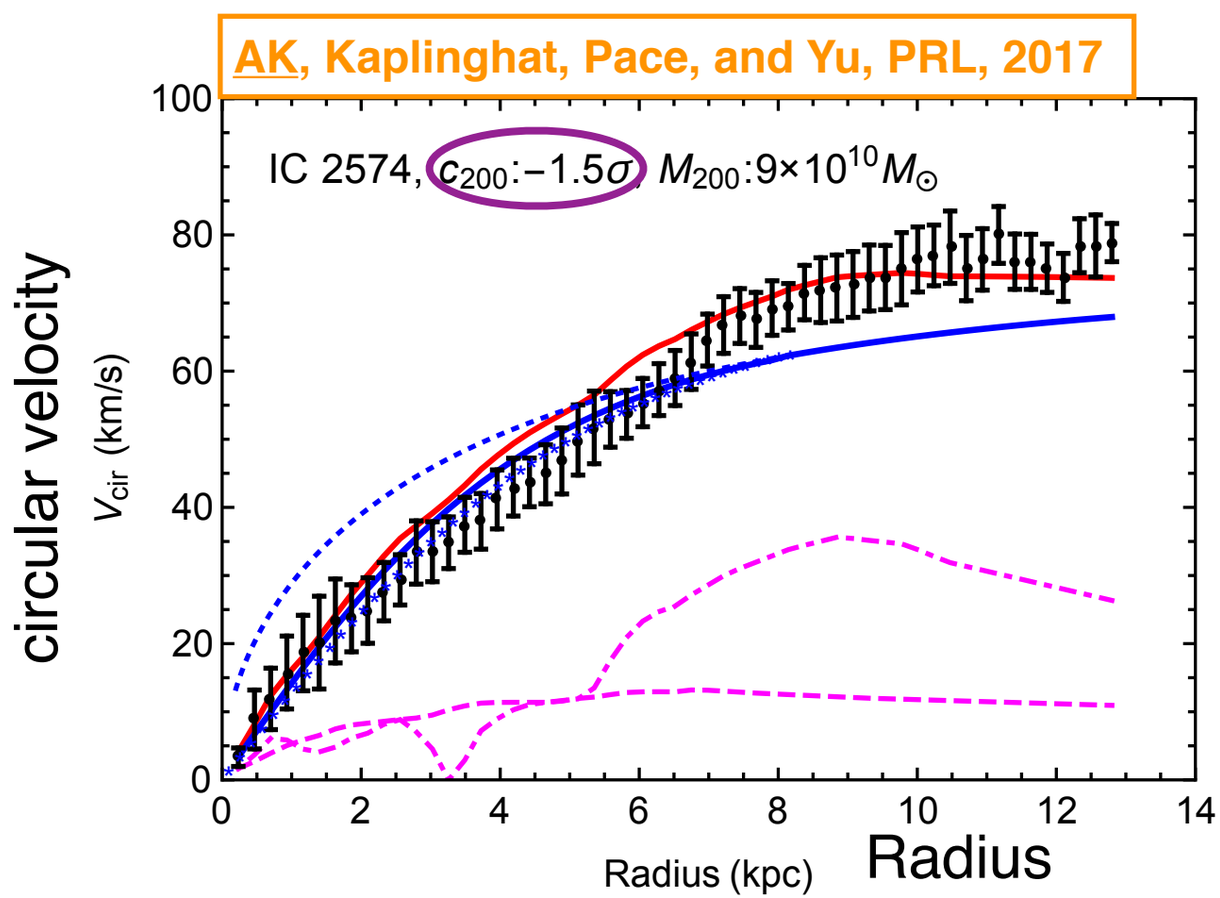
- compact → redistribute SIDM significantly
- extended → unchange SIDM distribution

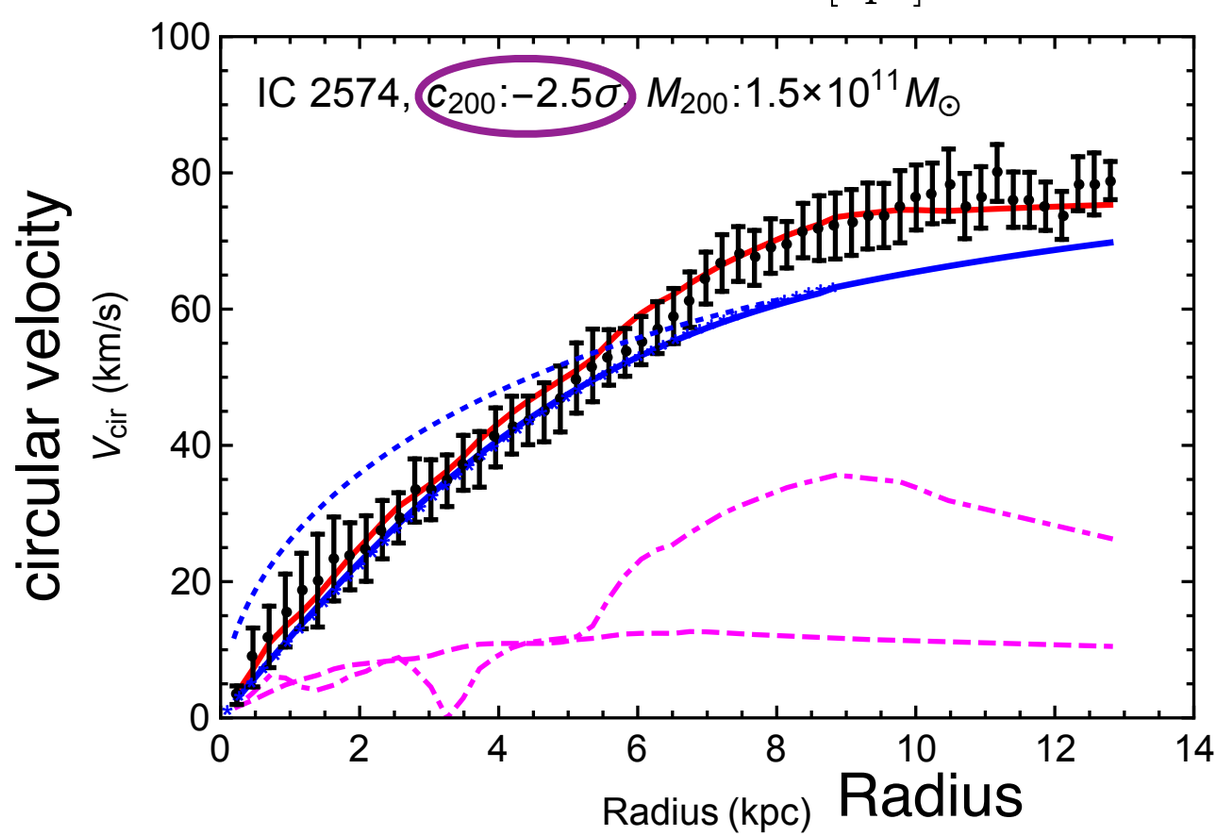


Intrinsic scatter

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







Summary

Asymmetric composite DM is a plausible framework

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

Simple QCD×QED-like dark sector as a working example

- right-handed neutrino: see-saw mechanisms, thermal leptogenesis, generating portal operator
- dark photon decay: transferring dark sector entropy to SM sector
- kinetic mixing: mediating dark proton-proton scattering

Summary

DM nucleons can realize a velocity-dependent self-scattering cross section indicated by small-scale puzzles

- $\sigma/m \gtrsim 1\mathrm{cm}^2/\mathrm{g}$ for $v \sim 10\text{-}100\,\mathrm{km/s}$
- $\sigma/m \lesssim 0.1\mathrm{cm}^2/\mathrm{g}$ for $v \sim 1000\,\mathrm{km/s}$

New puzzle: diversity of inner rotation curves

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

Thank you for your attention

Explaining tiny kinetic mixing

Origin of tiny kinetic mixing $\epsilon \sim 10^{-10}$?

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

Grand unifications in both SM and dark sectors

$$SU(5) \qquad SU(4)$$

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

$$\overline{\mathbf{4}} : (\overline{d}', \overline{e}') \quad \widetilde{\mathbf{4}} : (\widetilde{d}', \widetilde{e}')$$

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

Σ: adjoint scalar

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

$$\sim m_C > M_R > 10^9\,{\rm GeV}$$

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 $|\widetilde{e}'|^2 |H|^2$

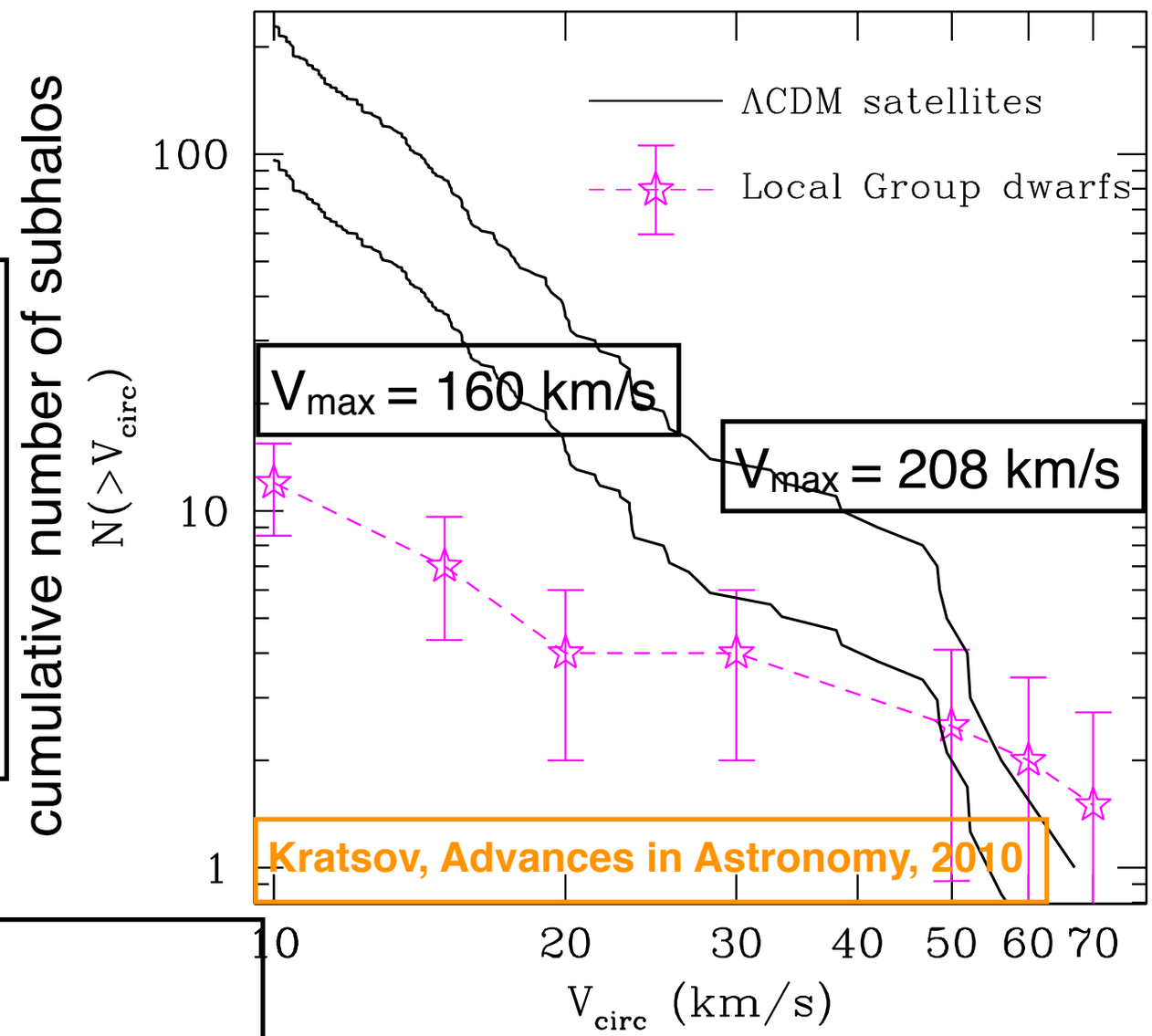
- DM direct detection through Higgs portal?

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



Kratsov, Advances in Astronomy, 2010

maximal circular velocity of subhalo

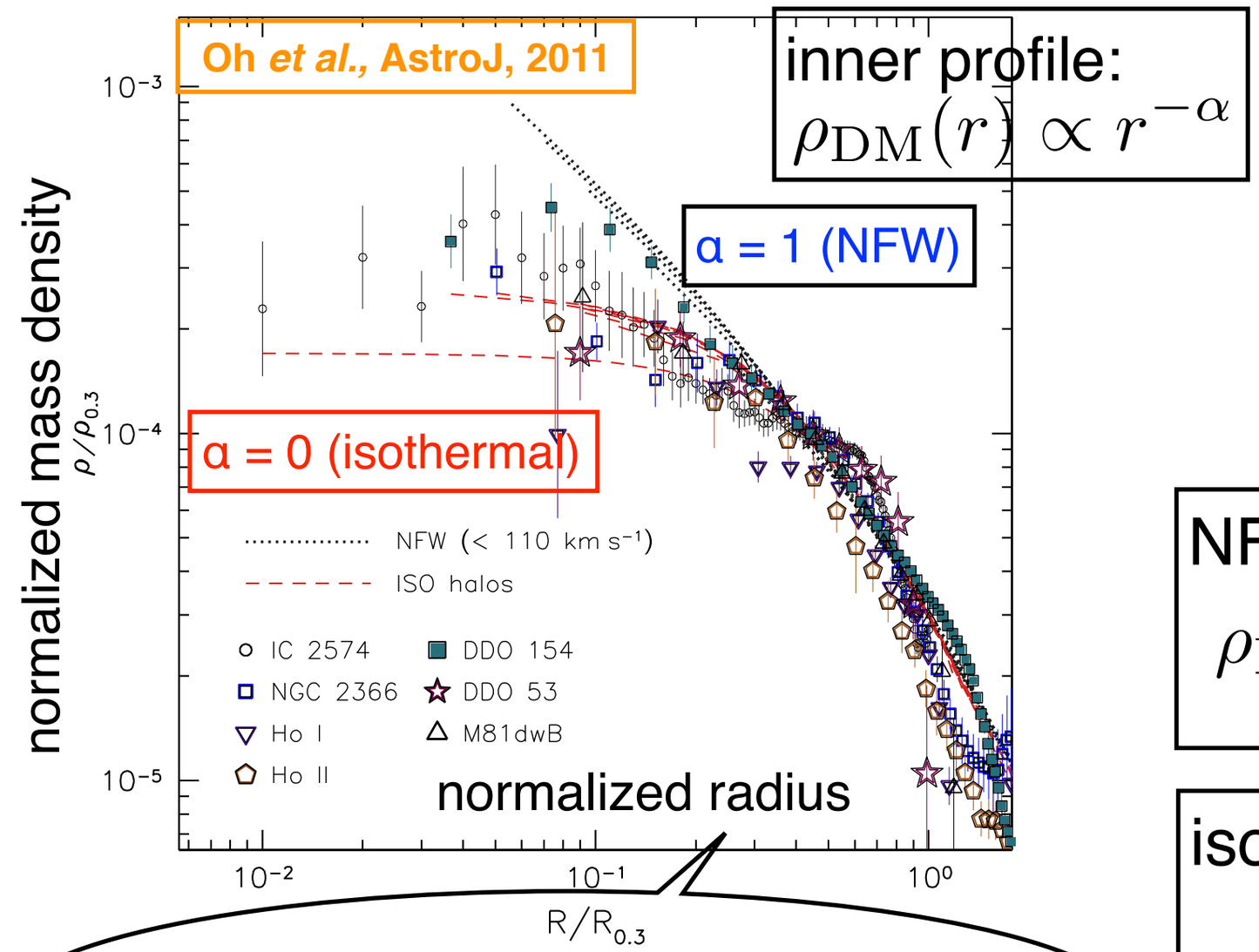
(maximum) circular velocity

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

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



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:

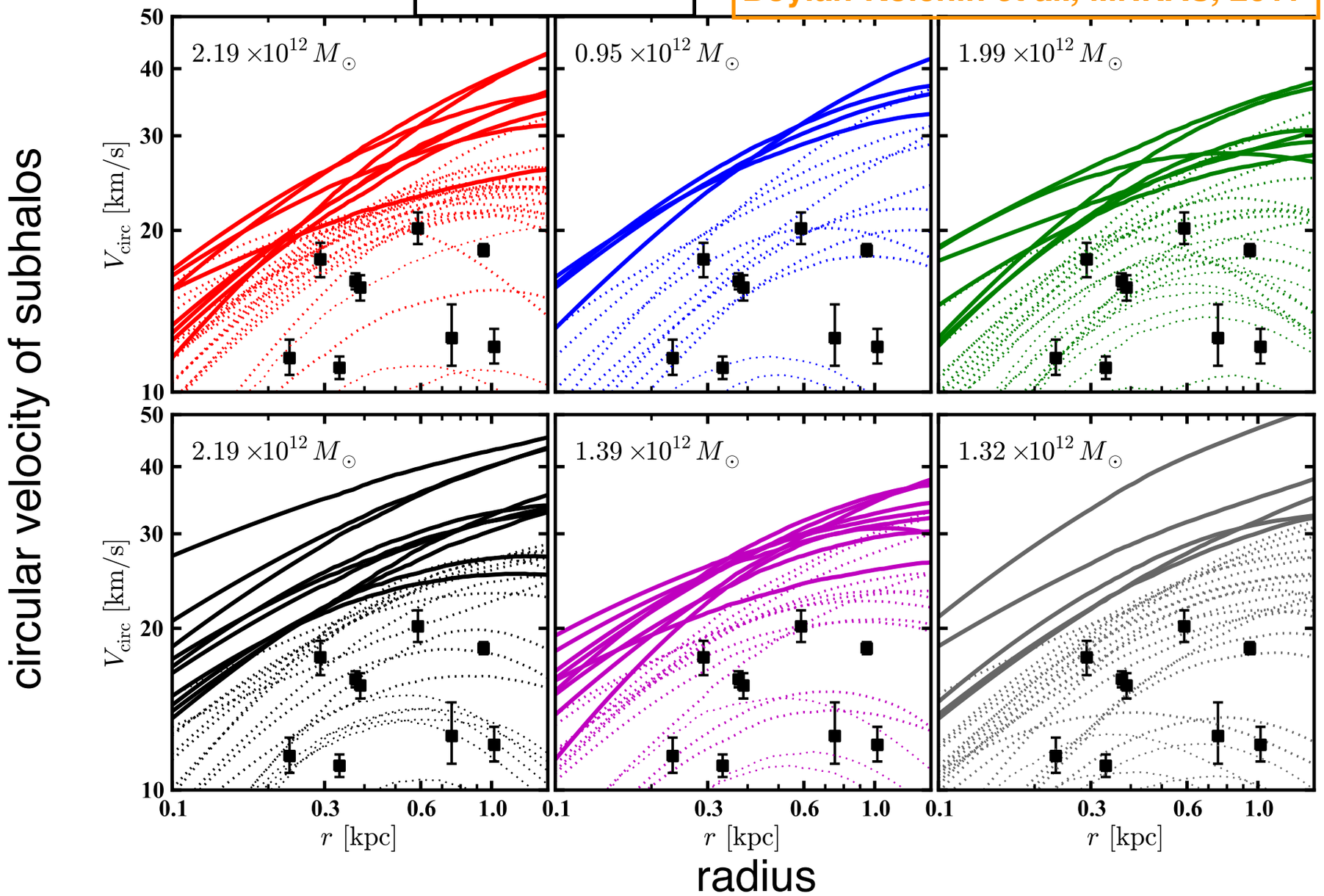
$$\rho_{\rm DM}(r) = \rho^0_{\rm DM} \begin{cases} 1 \ (r \ll r_0) \\ (r_0/r)^2 \ (r \gg r_0) \end{cases}$$

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

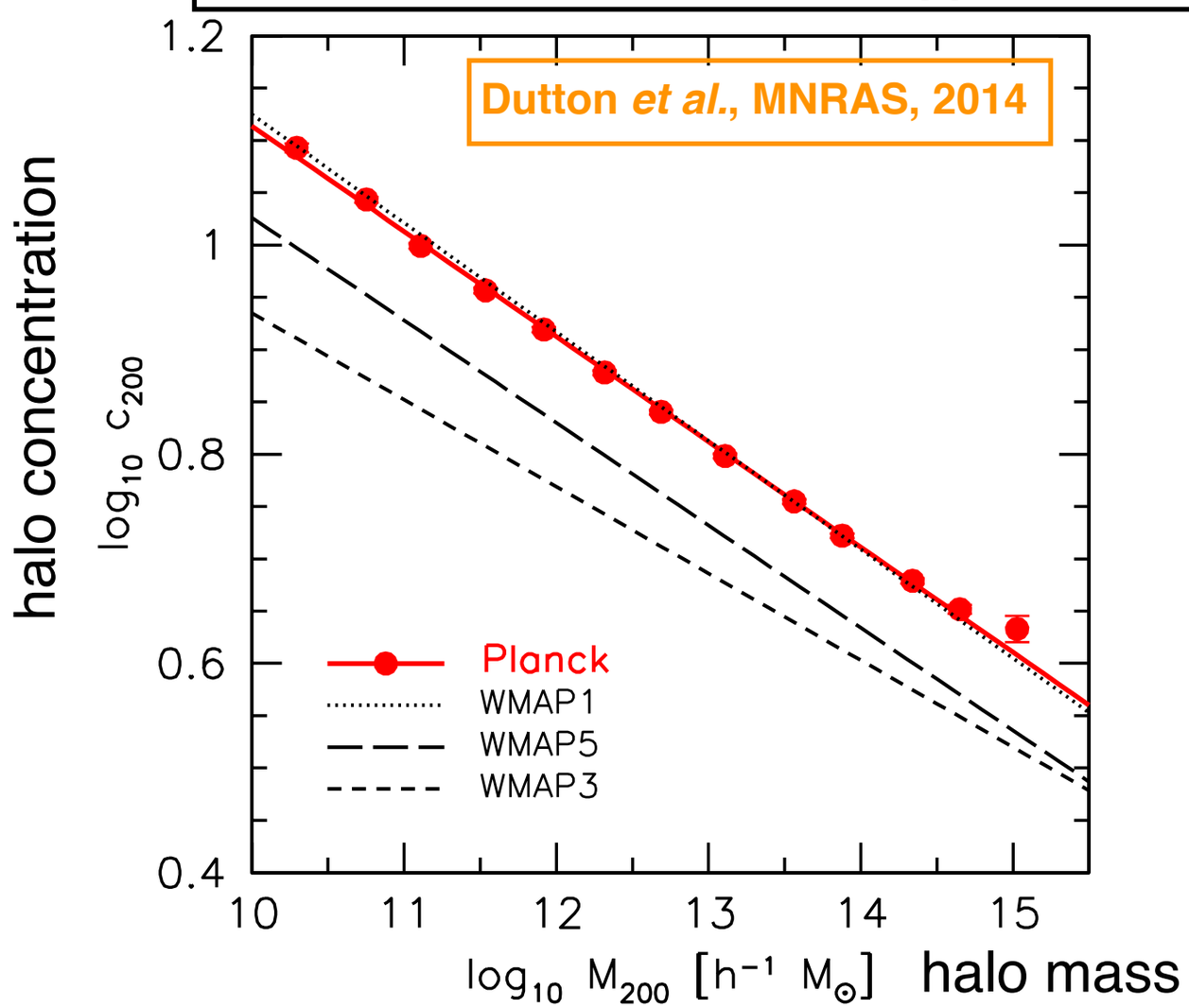
Why is a simulated rotation curve (almost) **DEFINITE** for a given V_{max}?
Two parameters for the NFW profile

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

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

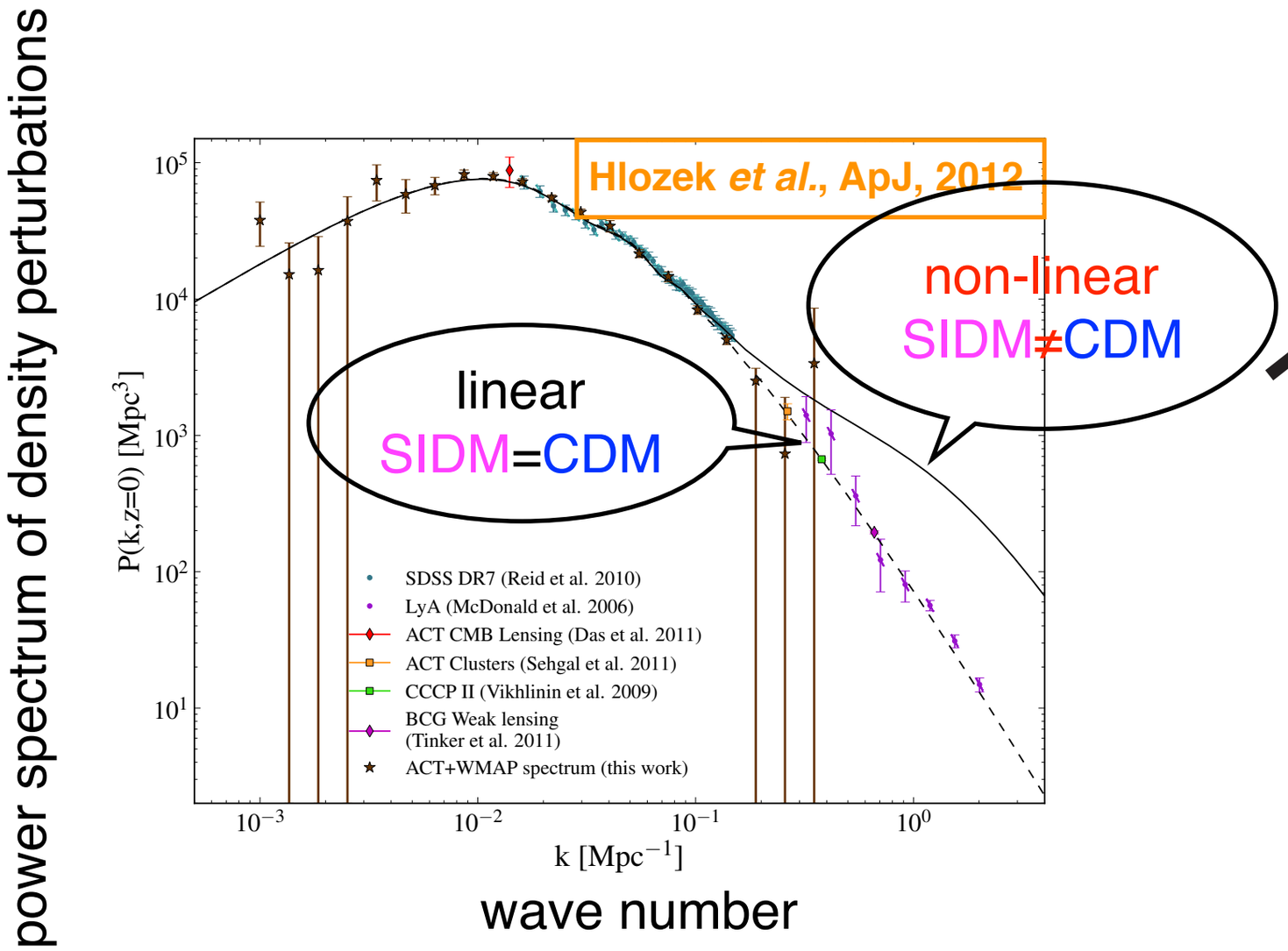


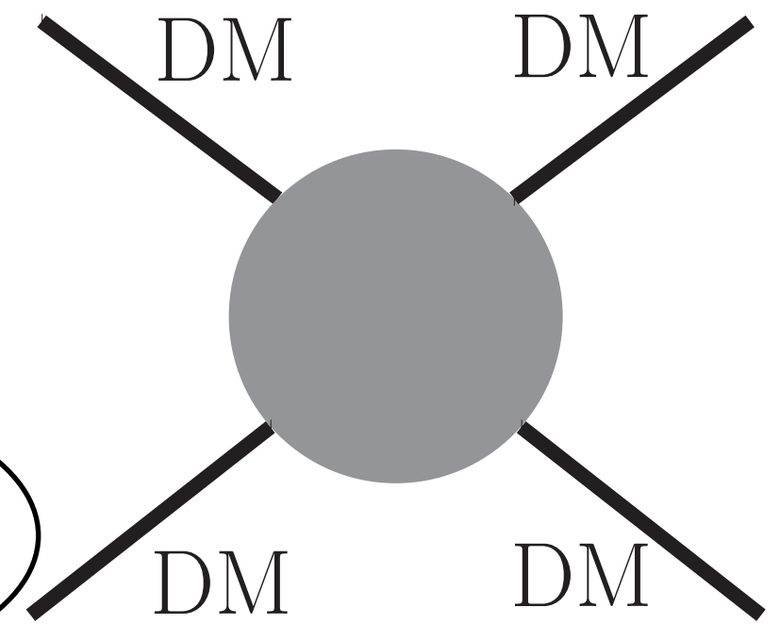
$$c_{200} = r_{200}/r_s$$

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

Dark matter self-interaction

Self-Interacting Dark Matter: SIDM





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

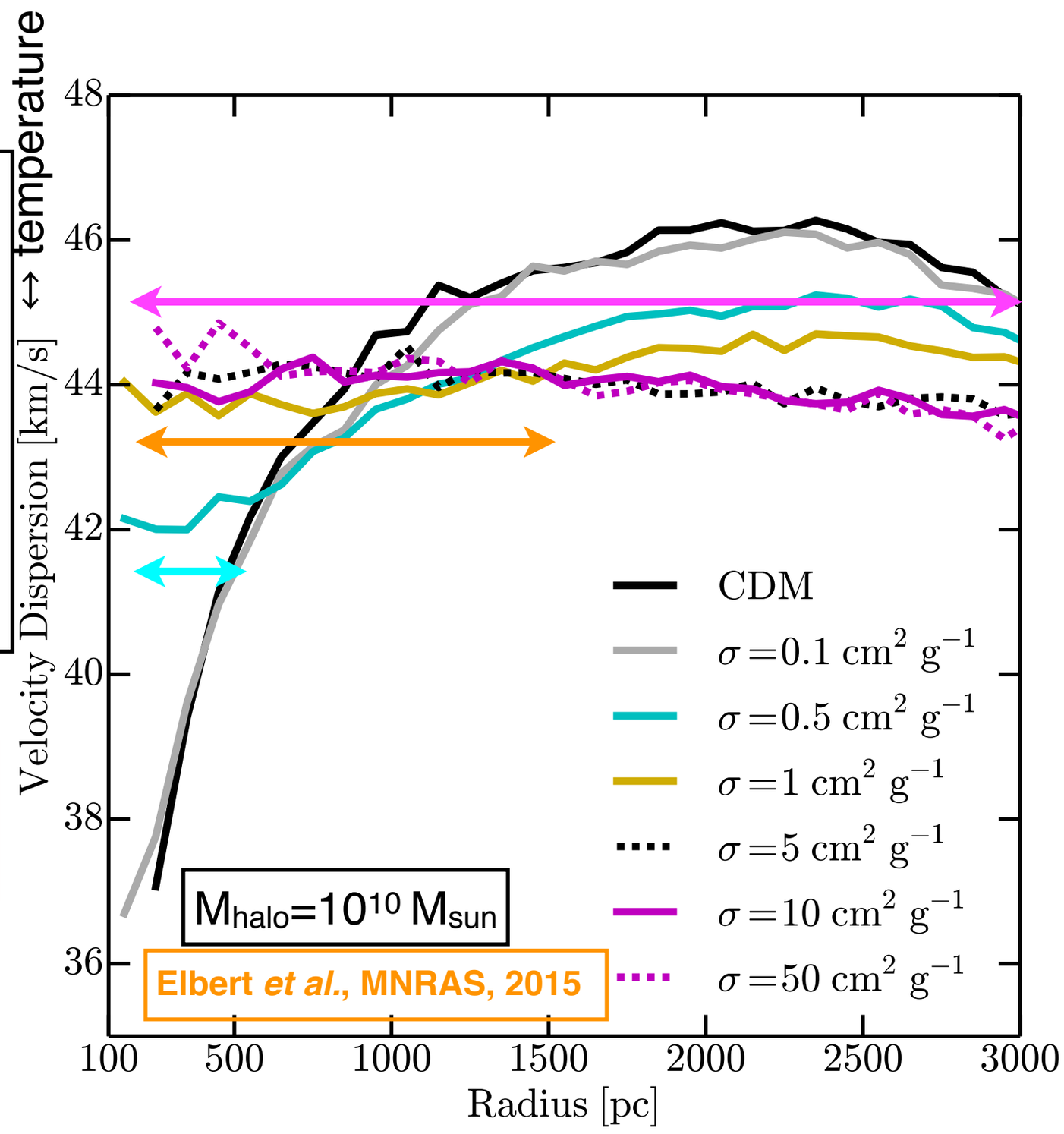
SIDM-only simulation

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

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

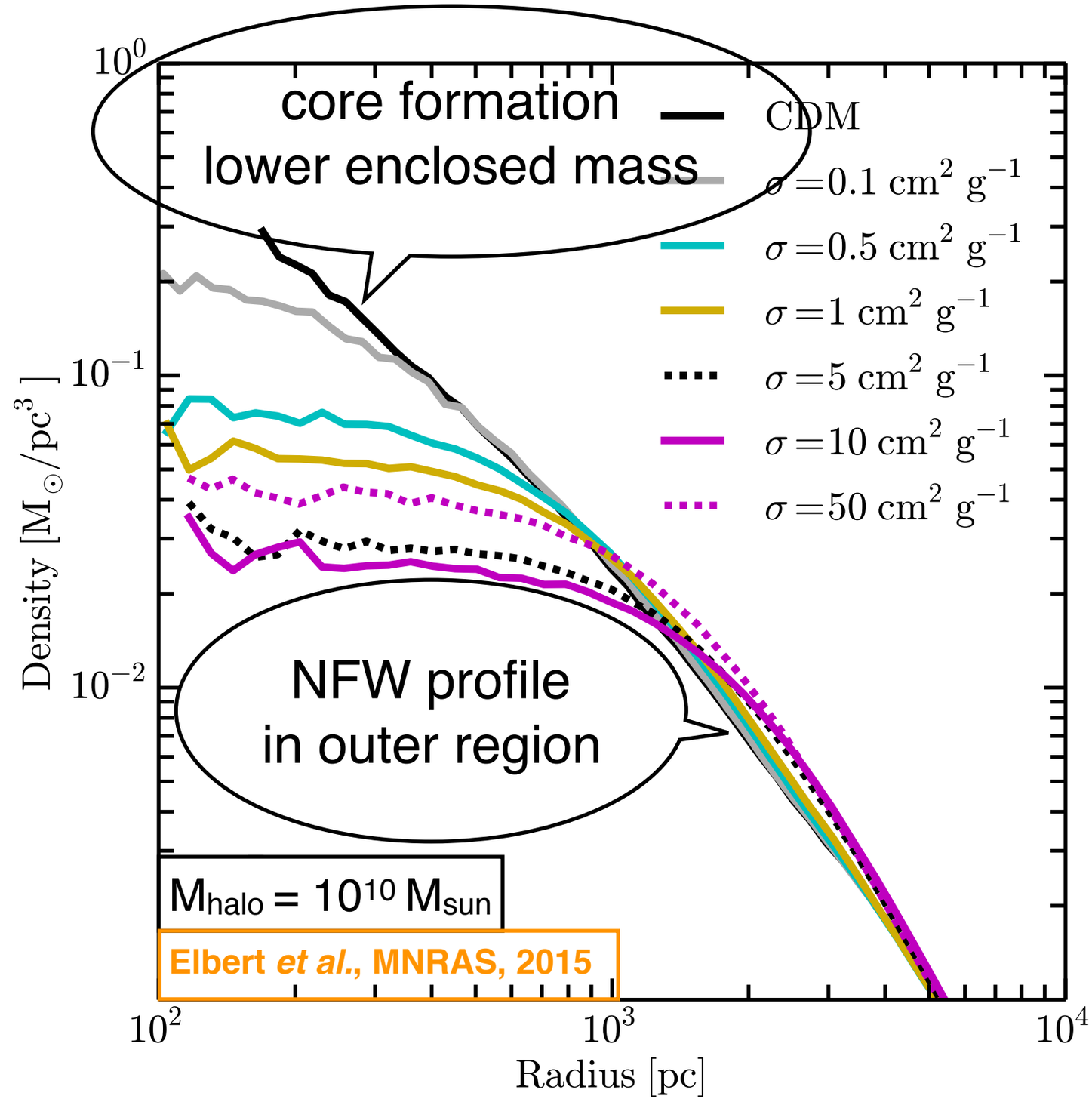


SIDM halo - mass density

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