Self-interacting dark matter, muon g-2, and neutrino physics in a gauged Lmu-Ltau model

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Based on
AK, Kunio Kaneta, Keisuke Yanagi, and Hai-bo Yu, JHEP, 2018

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Talk Plan

Part 1: Gauged $\mathrm{U}(1)_{L_\mu - L_\tau}$ extension of the standard model
- new gauge boson Z' and Higgs boson $\Phi \simeq (v_\Phi + \varphi)$
- muon anomalous magnetic moment $(g-2)_\mu$ and other constraints

Part 2: $\mathrm{U}(1)_{L_\mu - L_\tau}$ charged fermions N and $\bar{N}$ as dark matter
- φ mediates strong self-interaction in (dwarf) galaxies, while it diminishes toward galaxy clusters
- solving small-scale issues that are hard to explain in the conventional cold dark matter model

Part 3: Summary and implications for neutrino astrophysics
- IceCube dip
- supernova cooling

Part 1

Gauged $\mathrm{U}(1)_{L_\mu - L_\tau}$ extension of the standard model
- new gauge boson Z' and Higgs boson $\Phi \simeq (v_\Phi + \varphi)$
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Minimal $\mathrm{U}(1)_{L_\mu - L_\tau}$ extension

Gauge anomaly free $\mathrm{U}(1)_{L_\mu - L_\tau}$

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + g' Z'_\mu \left(L_2^\dagger \bar{\sigma}^\mu L_2 - L_3^\dagger \bar{\sigma}^\mu L_3 - \bar{\mu}^\dagger \bar{\sigma}^\mu \bar{\mu} + \bar{\tau}^\dagger \bar{\sigma}^\mu \bar{\tau} \right) - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} - \frac{1}{2} \epsilon Z'_{\mu\nu} B^{\mu\nu}$$
$$+ (D_\mu \Phi)^\dagger D^\mu \Phi - V(\Phi, H)$$

only the second (+1) and third (-1) generation leptons couple to a new gauge boson Z' ($\mathrm{U}(1)_{L_\mu - L_\tau}$ charge)

New Higgs boson Φ (-1)

$$V(\Phi, H) = -m_\Phi^2 |\Phi|^2 + \frac{1}{4} \lambda_\Phi |\Phi|^4 + \lambda_{\Phi H} |\Phi|^2 |H|^2$$

develops vacuum expectation value (VEV) $\Phi \simeq (v_\Phi + \varphi)$

→ $m_\varphi = \sqrt{\lambda_\Phi / 2}\, v_\Phi$, $m_{Z'} = g' v_\Phi$

Turn off kinetic mixing $\epsilon = 0$ and Higgs portal $\lambda_{\Phi H} = 0$ for simplicity

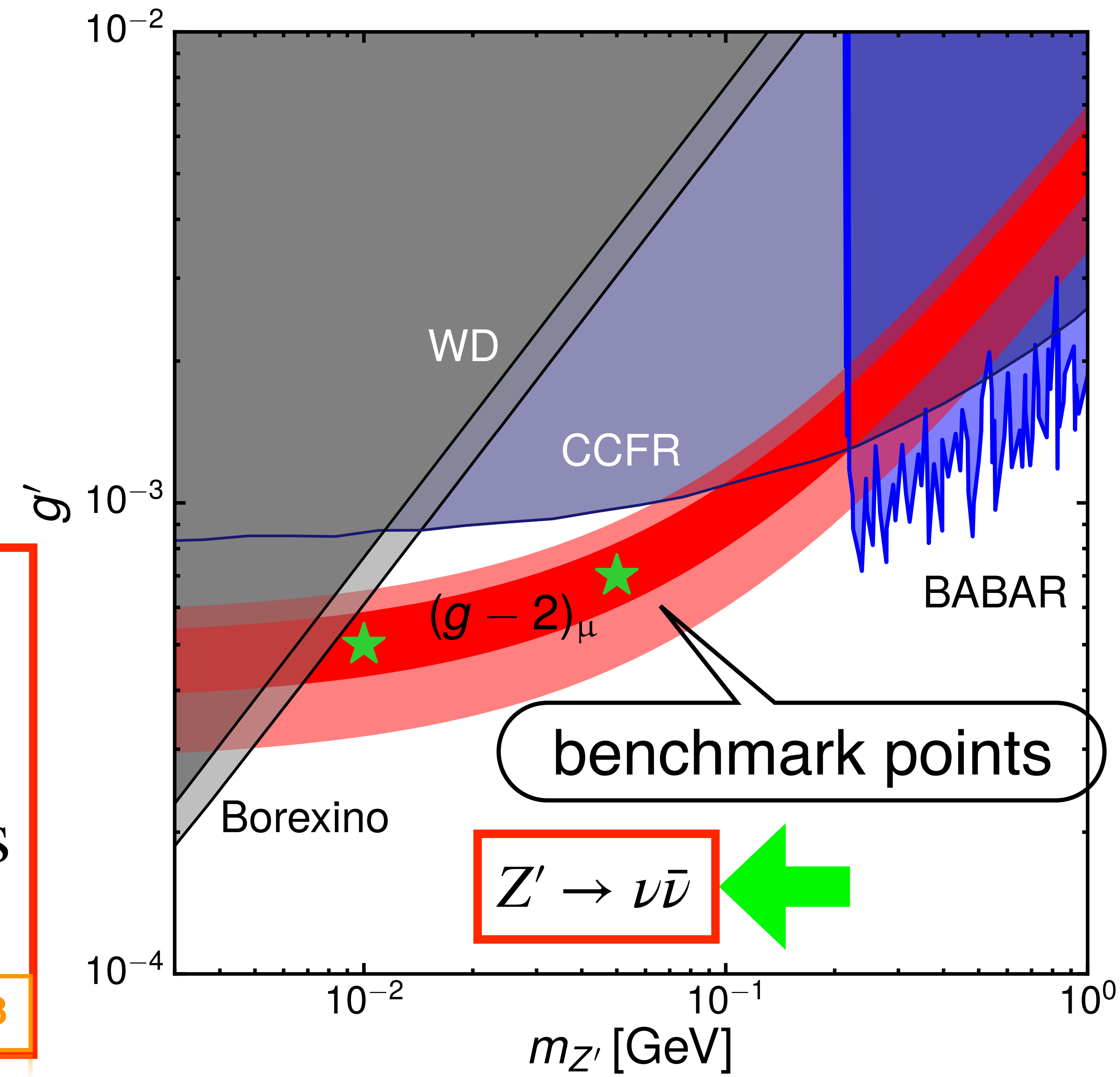
Z'-A mixing at the 1-loop level: $\epsilon_{AZ'} = -\dfrac{e g'}{12\pi^2} \ln \left(\dfrac{m_\tau^2}{m_\mu^2} \right)$

Muon g-2 and other tests

3σ discrepancy between the SM prediction and measurement

$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \times 10^{-10}$ $\quad a_\mu = (g-2)_\mu/2$ **Hagiwara *et al.*, J. Phys. G, 2011**

explained by Z' contribution **Baek *et al.*, PRD, 2001**



muon beam dump experiment (NA64μ) will cover the whole plane!

$\mu Z \to \mu Z Z' \to \mu Z + \text{invisibles}$

(Z : target nuclei)

Gninenko *et al.*, arXiv:1801.10448

Part 2

$\mathrm{U}(1)_{L_\mu - L_\tau}$ charged fermions N and $\bar{N}$ as dark matter
- φ mediates strong self-interaction in (dwarf) galaxies, while it diminishes toward galaxy clusters
- solving small-scale issues that are hard to explain in the conventional cold dark matter model

$\mathrm{U}(1)_{L_\mu - L_\tau}$ model with dark matter

Add a vector-like pair of SM singlet fermions
$N(+1/2)$ and $\bar{N}(-1/2)$ ($\mathrm{U}(1)_{L_\mu - L_\tau}$ charge)

$$\mathscr{L} = \mathscr{L}_{\text{minimal } \mathrm{U}(1)_{L_\mu - L_\tau}} + iN^\dagger \bar{\sigma}^\mu D_\mu N + i\bar{N}^\dagger \bar{\sigma}^\mu D_\mu \bar{N}$$
$$- m_N N\bar{N} - \frac{1}{2} y_N \Phi N N - \frac{1}{2} y_{\bar{N}} \Phi^* \bar{N}\bar{N} + \mathrm{h.c.}$$

VEV of $\Phi(-1)$: $\mathrm{U}(1)_{L_\mu - L_\tau} \to Z_2$
($v_\Phi = 20$ and $70\,\mathrm{GeV}$ for benchmark points)
stabilize the lightest mass eigenstate N_1 as dark matter

$$-\mathscr{L}_{\mathrm{mass}} = \frac{1}{2} \begin{pmatrix} N & \bar{N} \end{pmatrix} \begin{pmatrix} y_N \frac{v_\Phi}{\sqrt{2}} & m_N \\ m_N & y_{\bar{N}} \frac{v_\Phi}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} N \\ \bar{N} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} N_1 & N_2 \end{pmatrix} \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix} \begin{pmatrix} N_1 \\ N_2 \end{pmatrix}$$

where $\begin{pmatrix} N_1 \\ N_2 \end{pmatrix} = U \begin{pmatrix} N \\ \bar{N} \end{pmatrix}$ and $0 \le M_1 \le M_2$

Pseudo-Dirac case

Consider a C- and P-conserving pseudo-Dirac case:

$$m_N/v_\Phi \gg y_N = y_{\bar{N}} \equiv y > 0$$

$N_1 = (N - \bar{N})/(\sqrt{2}i)$ and $N_2 = (N + \bar{N})/\sqrt{2}$

$M_1 \approx m_N - y v_\Phi/\sqrt{2}$ and $M_2 \approx m_N + y v_\Phi/\sqrt{2}$

$$\mathscr{L} \supset -\frac{y}{2\sqrt{2}}\varphi\left(-\overline{N}_1 N_1 + \overline{N}_2 N_2\right) + ig' Q_N Z'_\mu \overline{N}_2 \gamma^\mu N_1$$

Yukawa interaction
- determine y by the relic abundance
- p-wave self-annihilation and s-wave co-annihilation

$(+\varphi \to Z'\nu\bar{\nu}$ and $Z' \to \nu\bar{\nu})$→ indirect detection is not constraining
- **self-interaction!**

Z' coupling (+Z'-A mixing)
- inelastic scattering → direct detection is not constraining!

Self-scattering cross section

Transfer cross section in the partial wave expansion

$$\sigma_T = 4\pi \int_0^1 d\cos\theta\,(1-\cos\theta)\frac{d\sigma}{d\Omega}$$

Tulin *et al.*, PRD, 2013

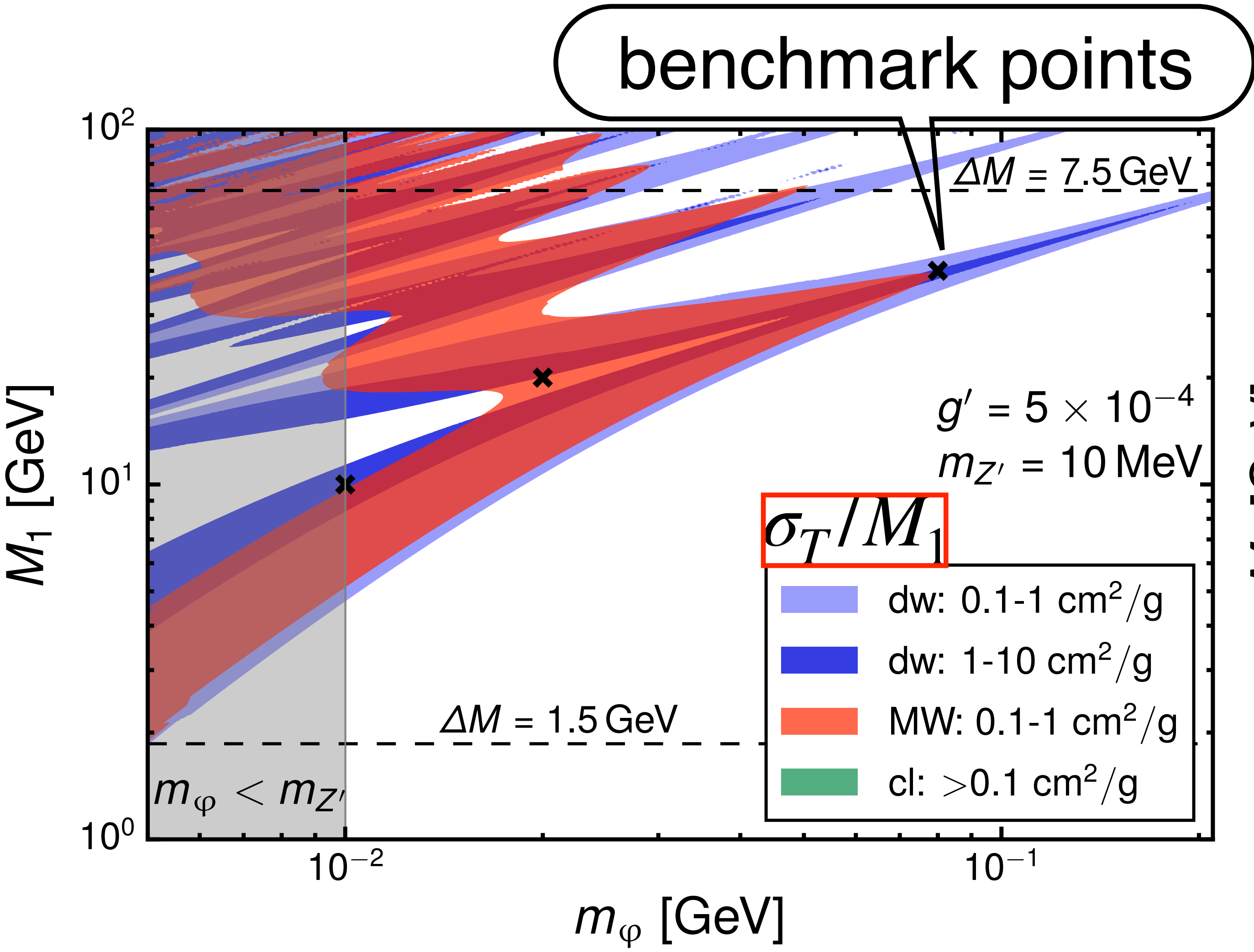
Kahlhoefer *et al.*, MNRAS, 2014

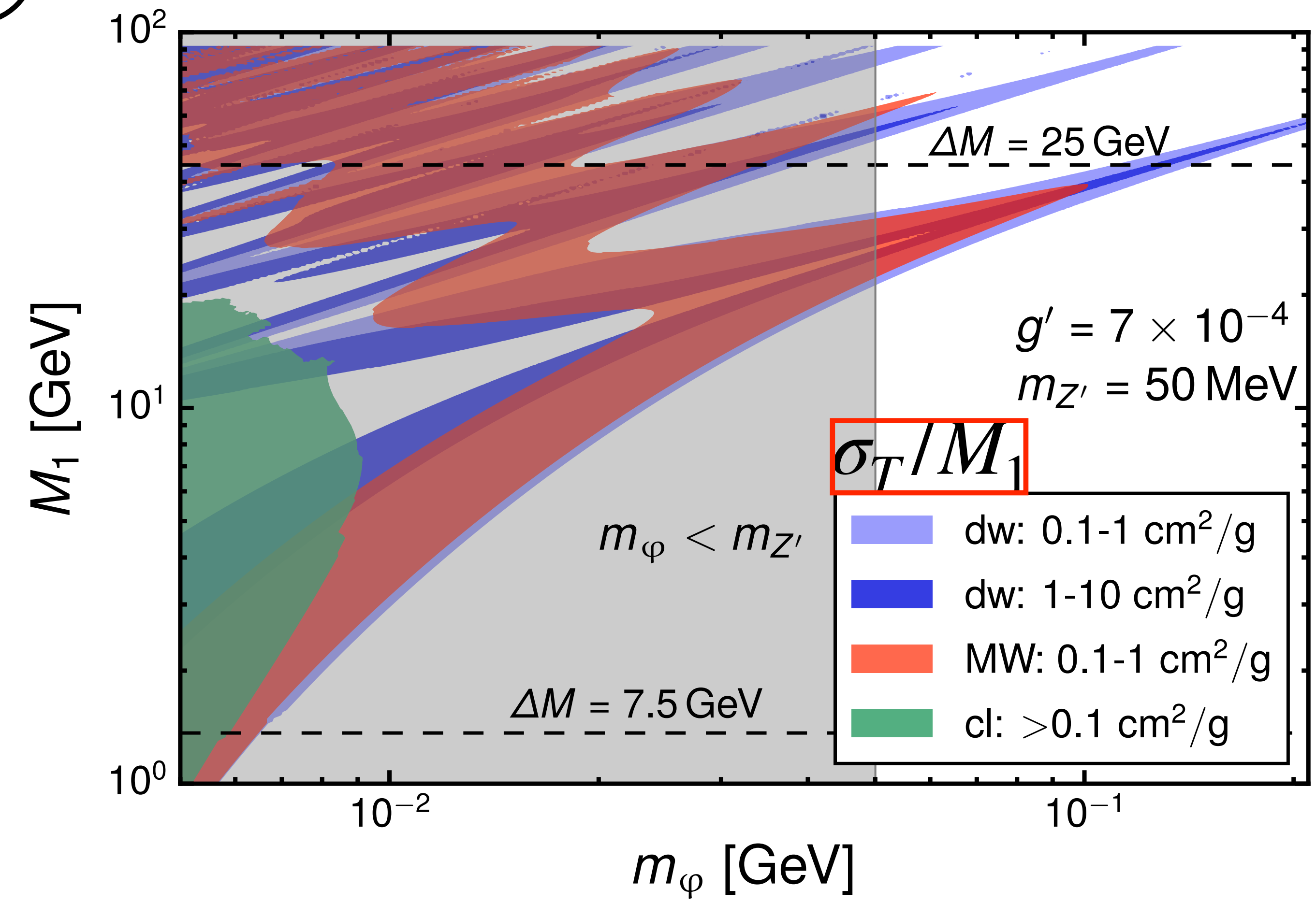
Kahlhoefer *et al.*, JCAP, 2017

as a function of the relative velocity $v_{\rm rel} = 30\,{\rm km/s}$ - dwarf galaxies

$v_{\rm rel} = 200\,{\rm km/s}$ - Milky-Way-size galaxies

$v_{\rm rel} = 1000\,{\rm km/s}$ - galaxy clusters





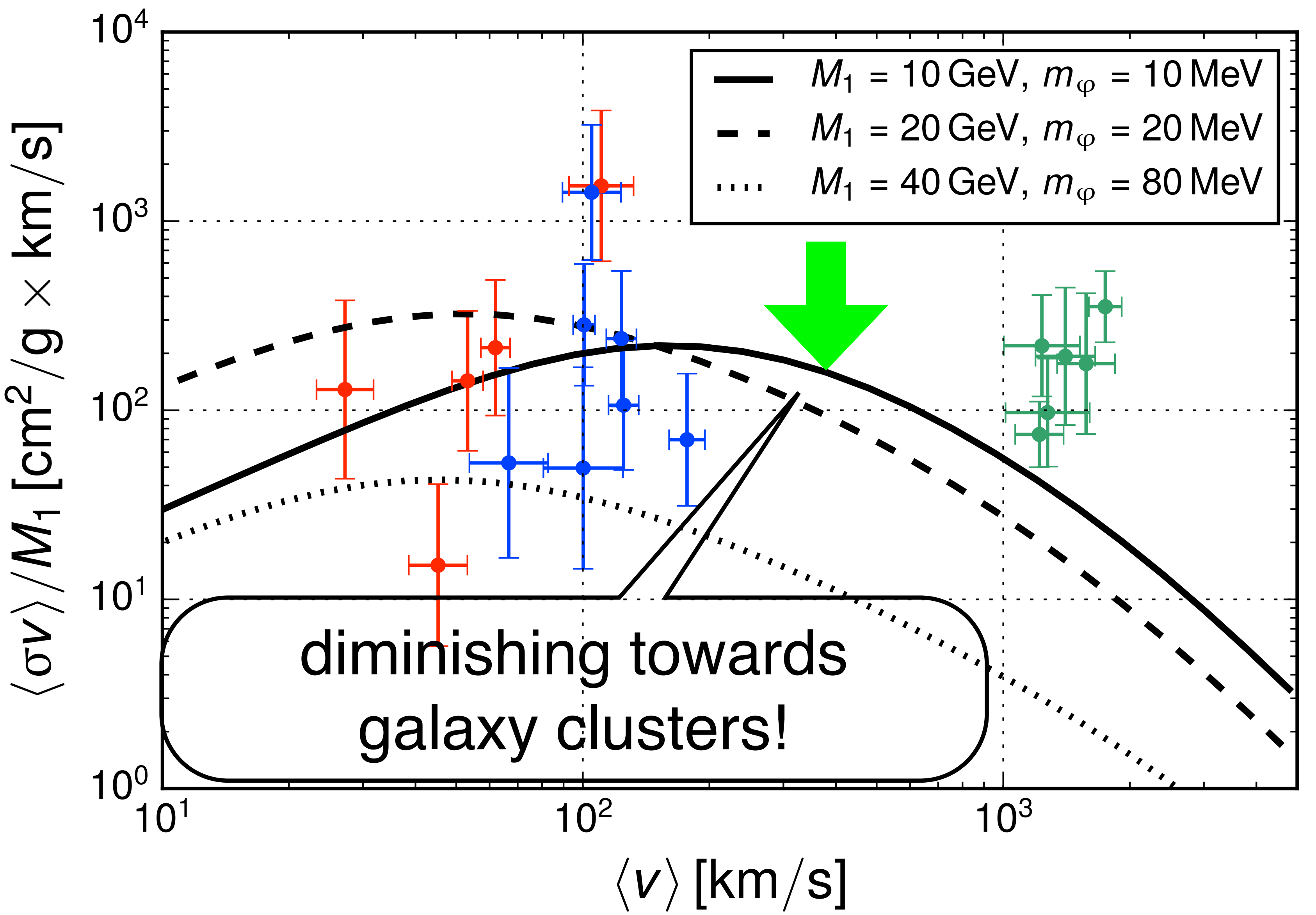
Solving small-scale issues

$\sigma_T/M_1 \sim 1\ \mathrm{cm}^2/\mathrm{g}$ changes the dark matter density profile in inner halos
→ explains a diversity of galactic rotation curves in inner shape
that is hard to understand in the collisionless cold dark matter model

Tulin *et al.*, Phys. Rept., 2018 | AK, Kaplinghat, Pace, Yu, PRL, 2017

Inferred distribution-averaged cross section from
dwarf galaxies
low surface brightness galaxies
galaxy clusters

Kaplinghat *et al.*, PRL, 2016



Meanwhile it does not spoil the cold dark matter success in galaxy clusters

Part 3

Summary and implications for neutrino astrophysics
- IceCube dip
- supernova cooling

Summary

Simple $\mathrm{U}(1)_{L_\mu - L_\tau}$ extension of the standard model
- explain the discrepancy in $(g-2)_\mu$ by the Z' contribution
- parameter space will be tested in future facilities
- offer a dark matter candidate N_1 and force mediator φ
- strong self-interaction reconciles the small-scale issues of the cold dark matter model
- self-interaction diminishes towards galaxy clusters
- evade both direct and indirect detection constraints

Resonant self-scattering and IceCube dip

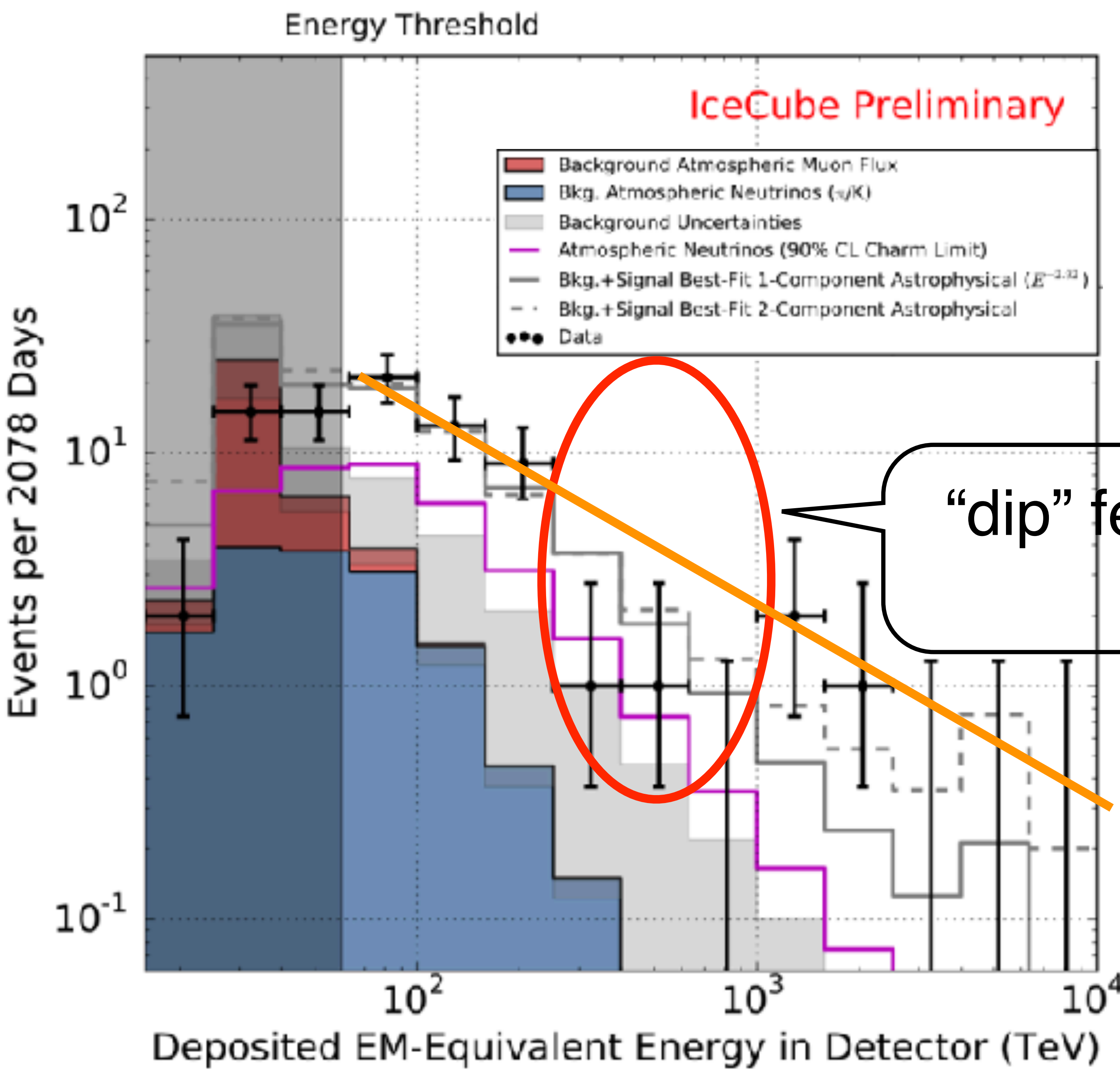
High-energy neutrino scattering with cosmic neutrino background is resonantly enhanced when $E_{\rm cm} \simeq m_{Z'}$: $\nu\bar{\nu} \to Z' \to \nu\bar{\nu}$

$$E_{\rm res} = 500\,{\rm TeV} \left(\frac{m_{Z'}}{10\,{\rm MeV}}\right)^2 \left(\frac{0.1\,{\rm eV}}{m_\nu}\right)$$

Araki *et al.*, PRD, 2015

Araki *et al.*, PRD, 2016

AK and Yu, PRD, 2015



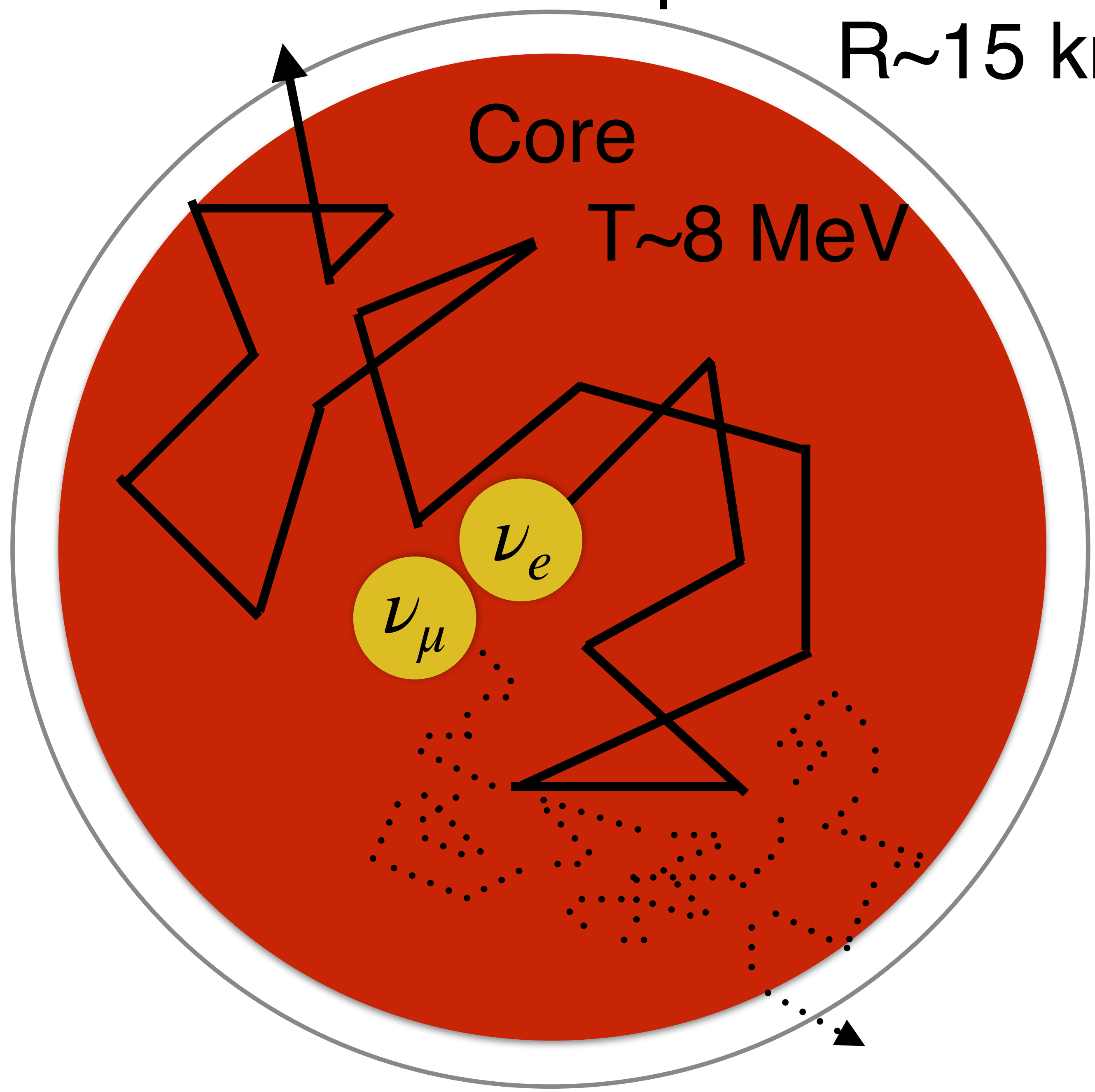
"dip" feature in the neutrino spectrum possible indication?

IceCube collaboration, arXiv:1710.01191

Supernova cooling

$\nu\bar{\nu} \to Z' \to \nu\bar{\nu}$ shortens the mean-free path of ν_μ and ν_τ
$\lambda \sim 0.01\,\mathrm{cm}$, while that of ν_e is unchanged $\lambda \sim 4\,\mathrm{m}$

AK and Yu, PRD, 2015



lengthen diffusion time of
ν_μ and ν_τ : $\tau \sim 10^5\,\mathrm{s}$
while that of ν_e is unchanged:
$\tau \sim 10\,\mathrm{s}$ (SN1987A)

Thank you for your attention

Experimental constraints

Z' contribution to $(g-2)_\mu$: $\Delta a_\mu^{Z'} \simeq 32 \times 10^{-10} \left(\frac{g'}{5 \times 10^{-4}} \right)^2$ for $m_{Z'} \ll m_\mu$

Evade existing constraints from

- neutrino trident production (CHARM-II, CCFR): $\nu N \to \nu N \mu \bar{\mu}$

  Altmannshofer *et al.*, PRL, 2014

- Υ decay (BABAR): $e\bar{e} \to \Upsilon \to \mu\bar{\mu}Z' \to \mu\bar{\mu}\mu\bar{\mu}$ **BaBar Collaboration, PRD, 2016**
- $^7\mathrm{Be}$ solar neutrino event rate: ν-e (Borexino) **Bellini *et al.*, PRL, 2011**
- white dwarf cooling: $\gamma \to \nu\bar{\nu}$ (γ: plasmon) **Dreiner *et al.*, PRD, 2013**

Caveat on Borexino and WD bounds:
although $\epsilon = 0$, Z'-A and Z'-Z mixings arise at one-loop level
→ Z' couples to the SM electromagnetic current $-\epsilon_{AZ'} e Z'_\mu J^\mu_{\mathrm{em}}$

$$\epsilon_{AZ'} = -\frac{eg'}{12\pi^2} \ln\left(\frac{m_\tau^2}{m_\mu^2}\right) \simeq 7.2 \times 10^{-6} \times \left(\frac{g'}{5 \times 10^{-4}}\right)$$

Cosmological constraint

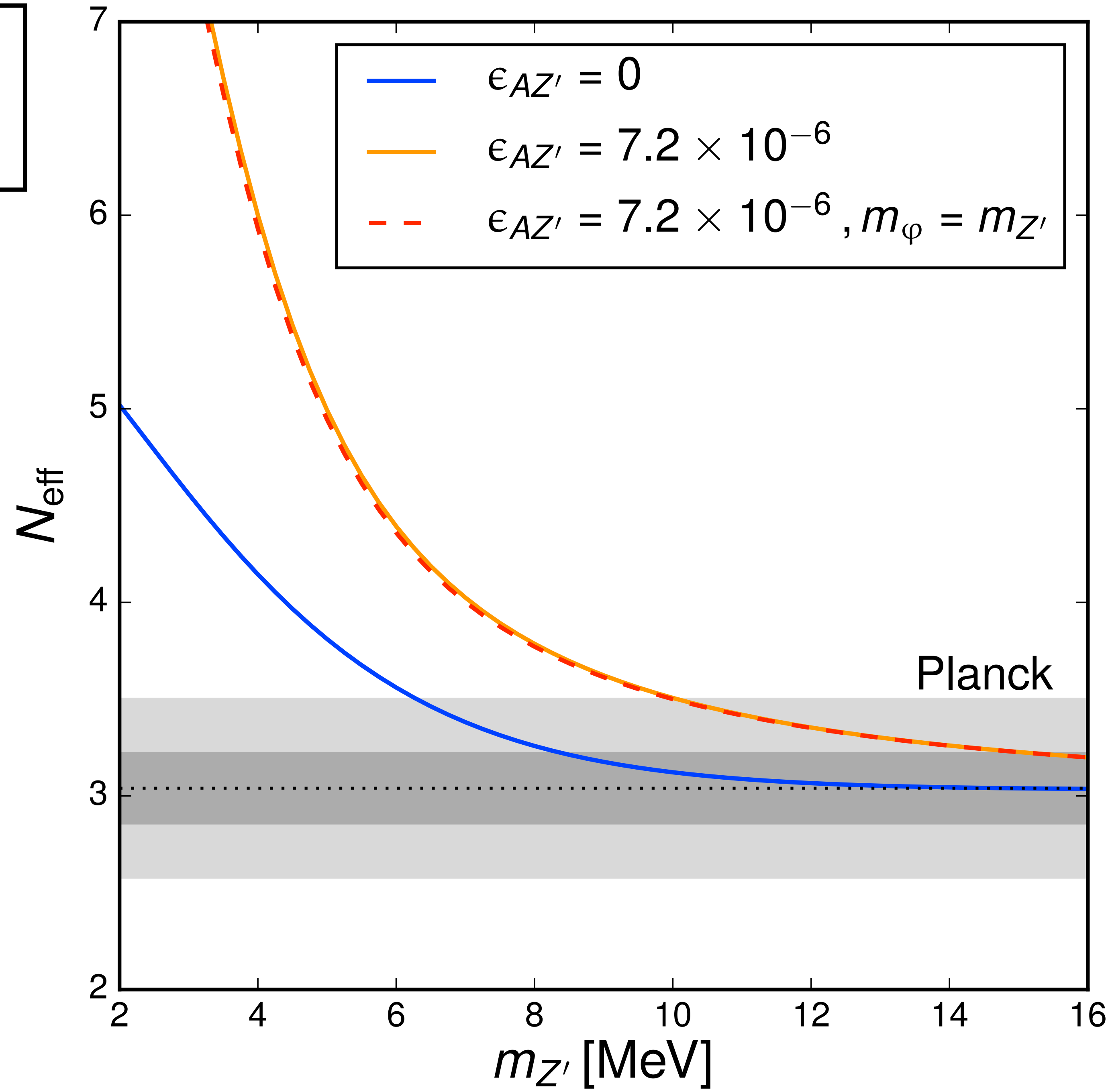
$Z' \to \nu\bar{\nu}$ heats only ν_μ and ν_τ after neutrino decoupling
$Z' \to e\bar{e}$ through Z'-A mixing transfer heats between (e, γ) and (ν_μ, ν_τ, Z')

change the effective number of neutrino degrees of freedom

$\varphi \to Z'\nu\bar{\nu}$ is sufficiently rapid for $m_\varphi \geq m_{Z'}$

Benchmark points ($m_{Z'} > 10\,\mathrm{MeV}$) satisfy $N_{\mathrm{eff}} < 3.5$

Planck Collaboration, A&A, 2015

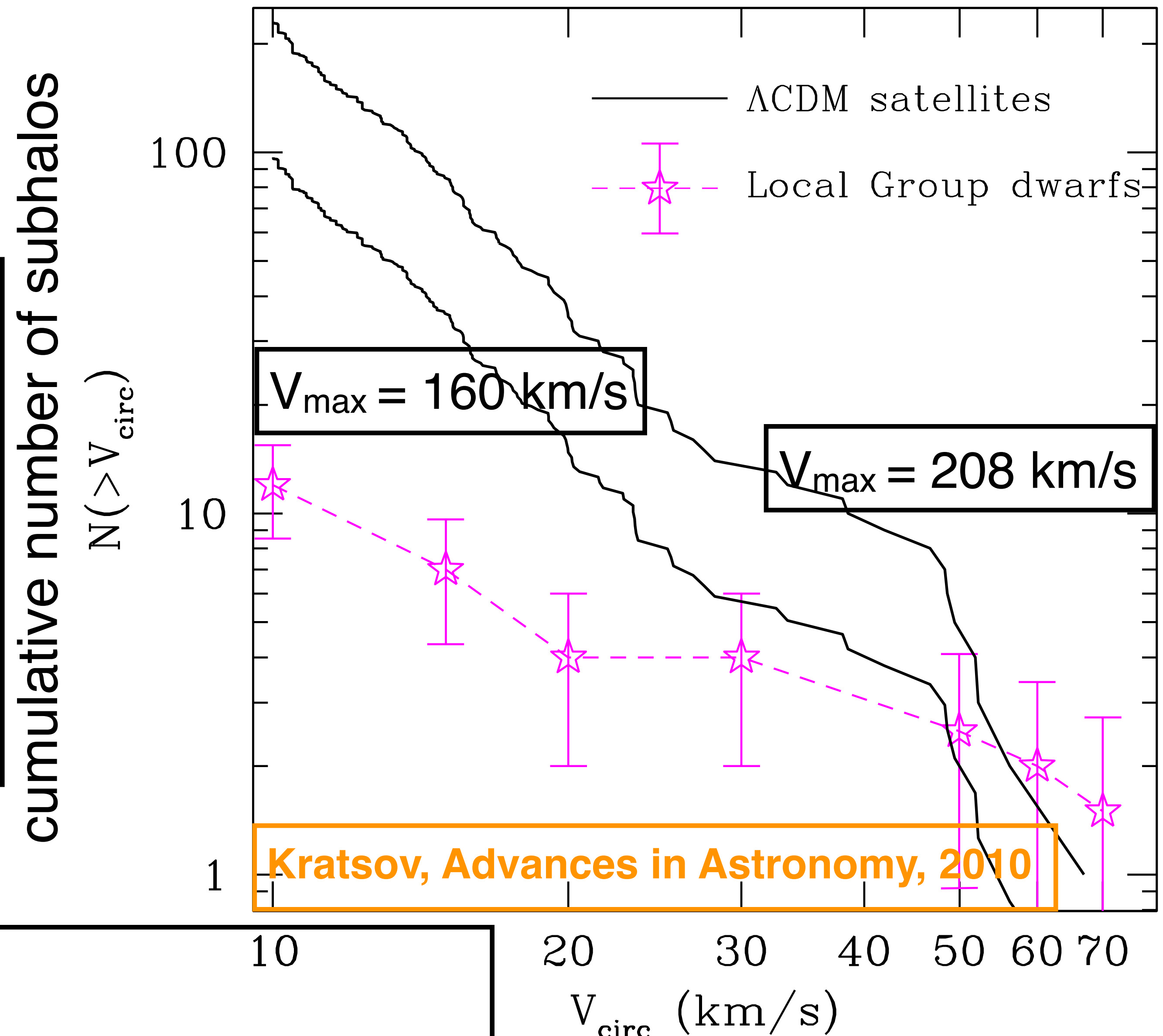


Small scale crisis I

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



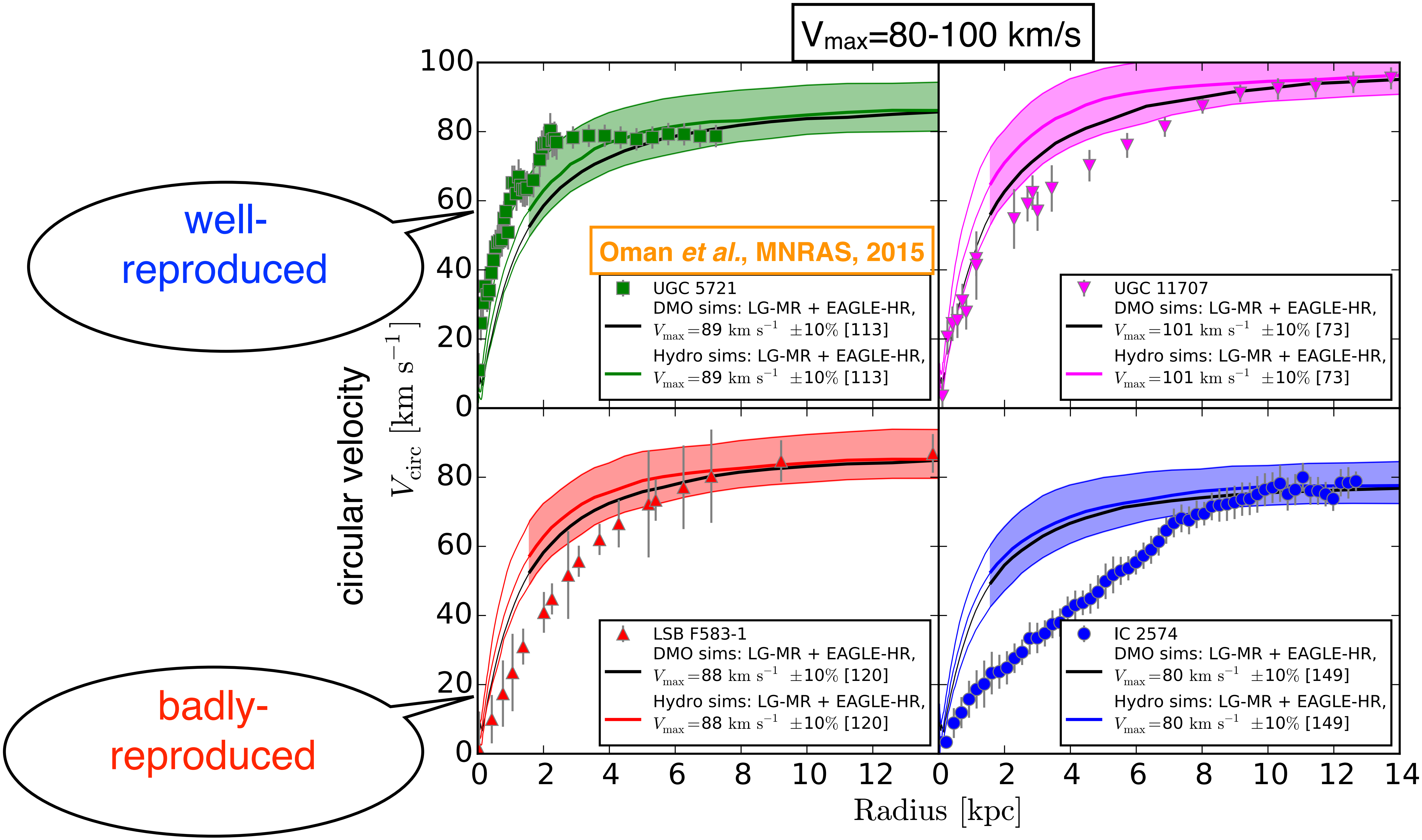
maximal circular velocity of subhalo

(maximum) circular velocity

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

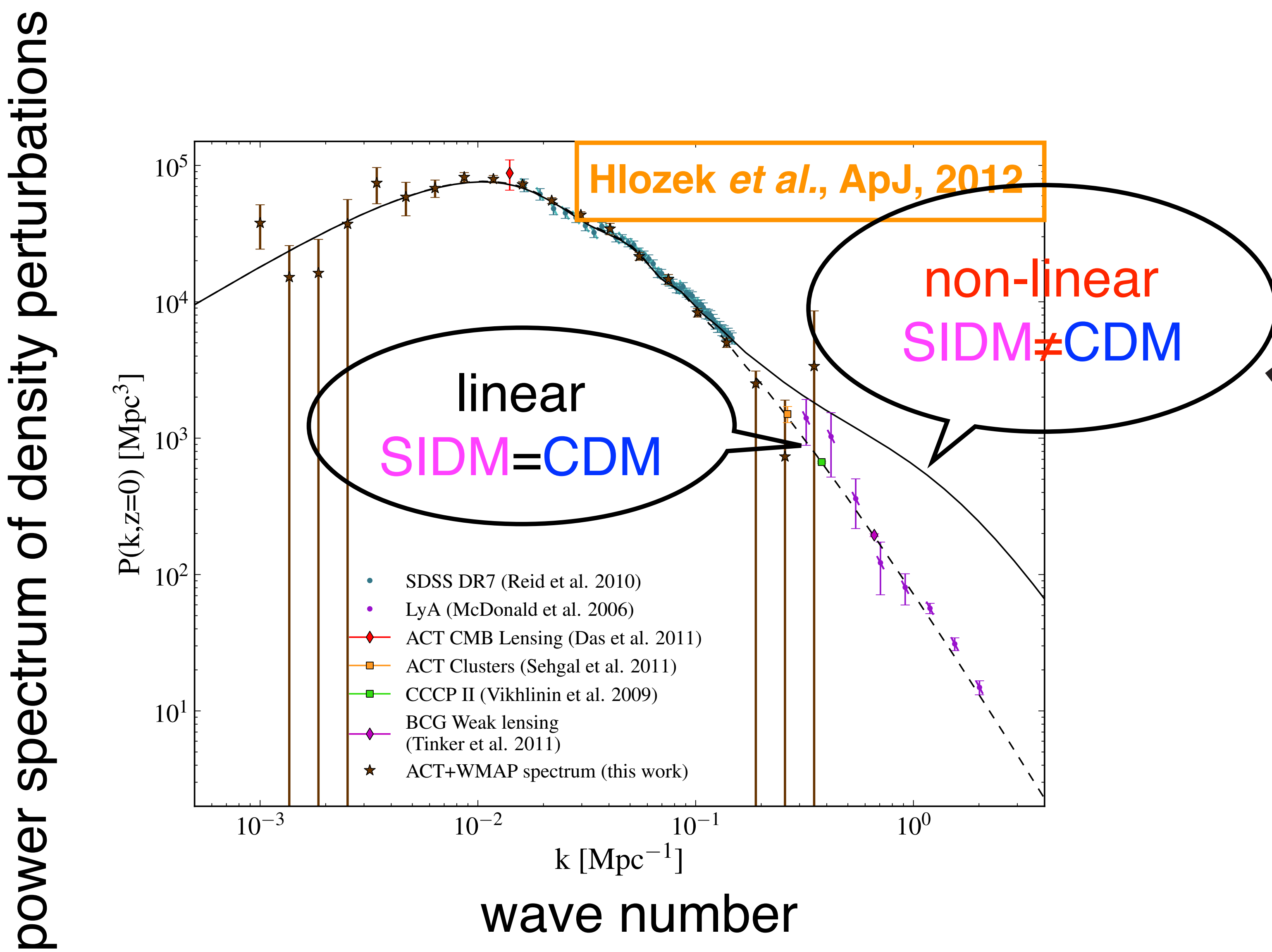
Small scale crisis II

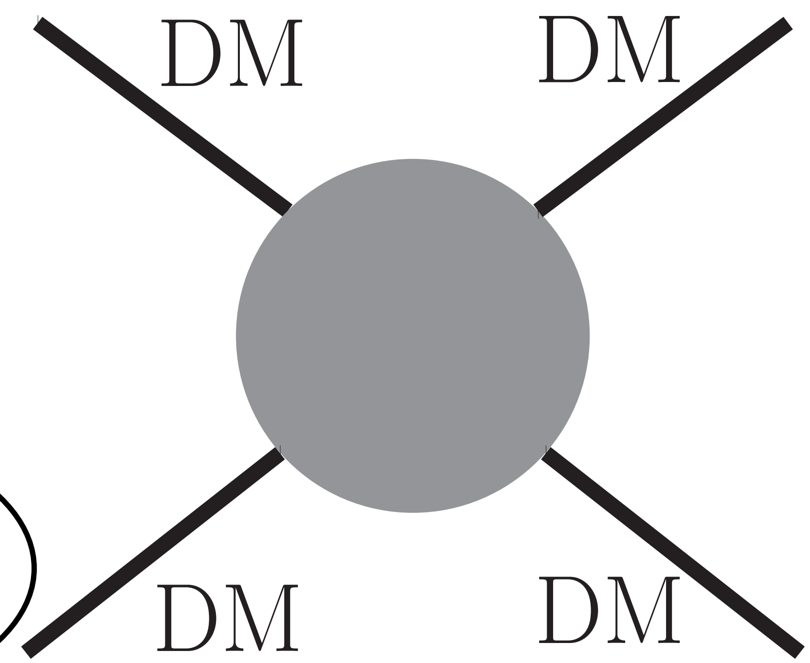
Unexpected diversity of rotation curves



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

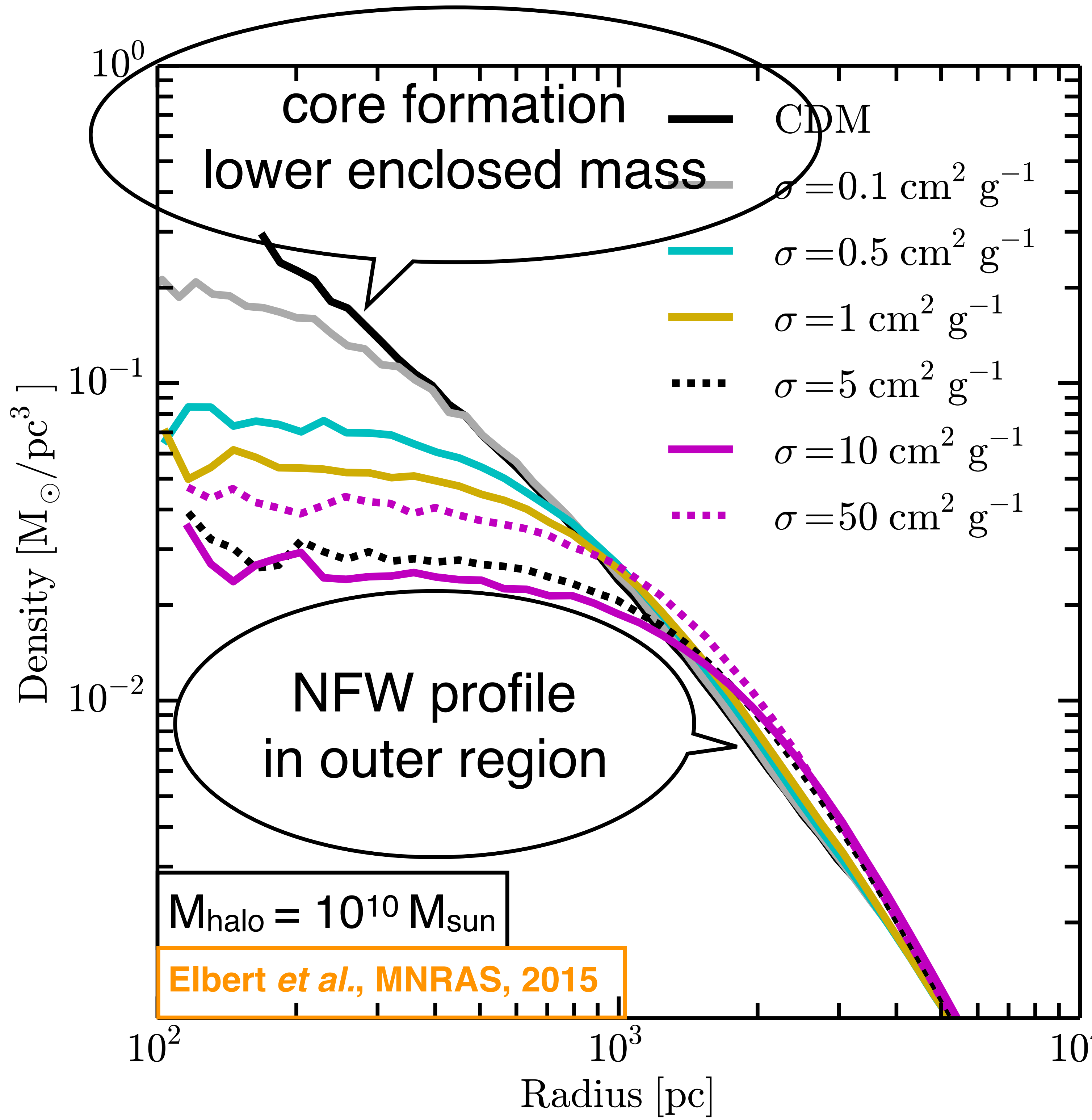
SIDM structure formation starts with
the same linear (initial) matter power spectra as CDM,
but self-interactions become important
as structure formation proceeds ↔ ρ increases

SIDM halo - 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 $\mathrm{cm^2/g}$ may solve the inner mass deficit problem

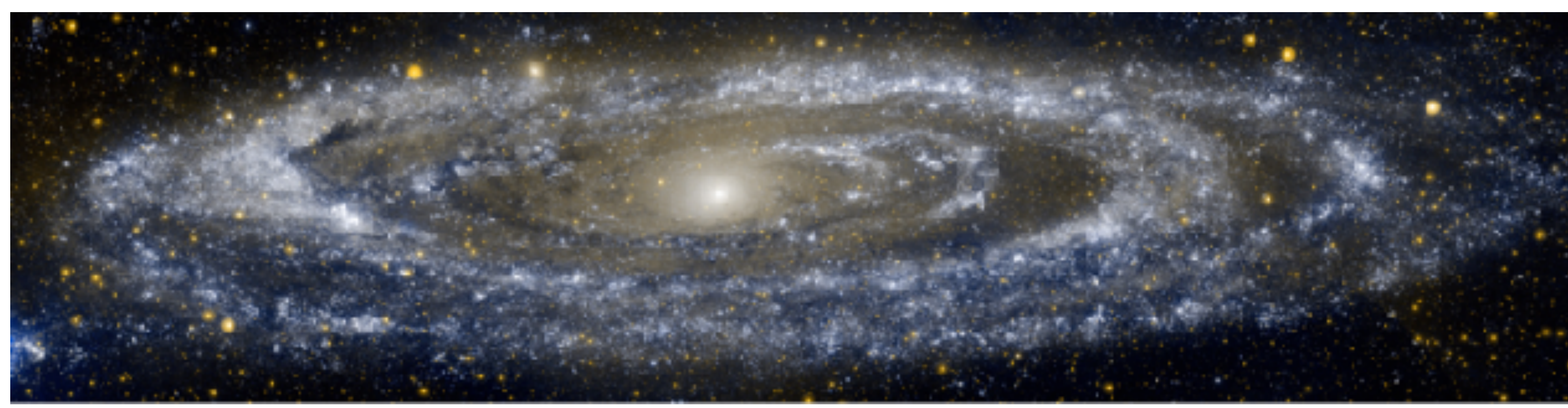
Origin of the diversity

How does SIDM solve the unexpected diversity problem?

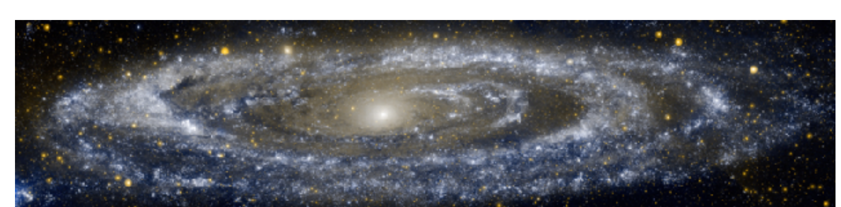
For a given cross section (σ/m = 3 cm^2/g in the following), SIDM halo profile is still definite and characterized by only one parameter V_{max}

Scatter in distributions of the baryons even among similar-size halos!

Extended stellar disk



Compact stellar disk



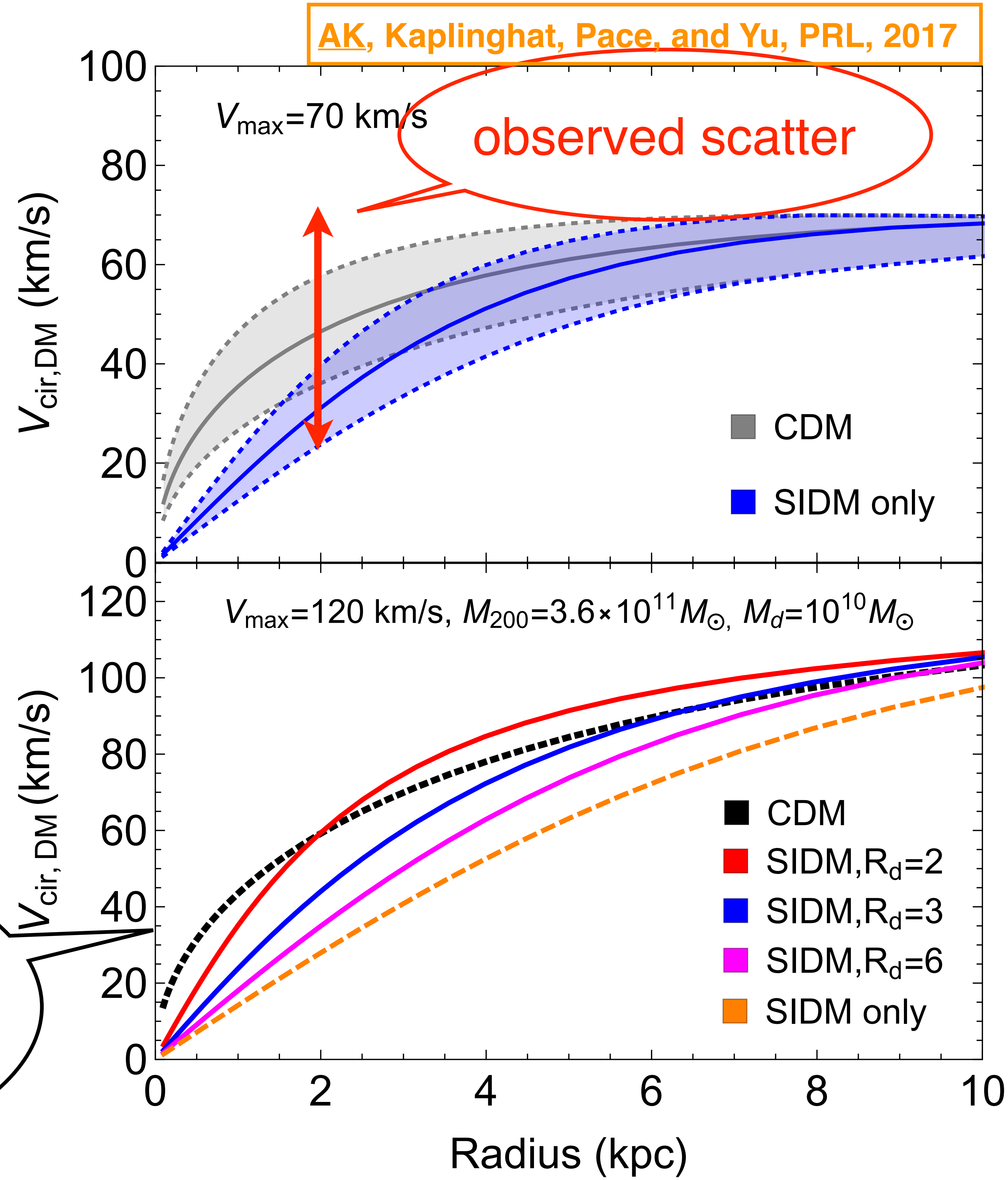
Influence of the baryons

Iso-thermal distribution from the Poisson equation:

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

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

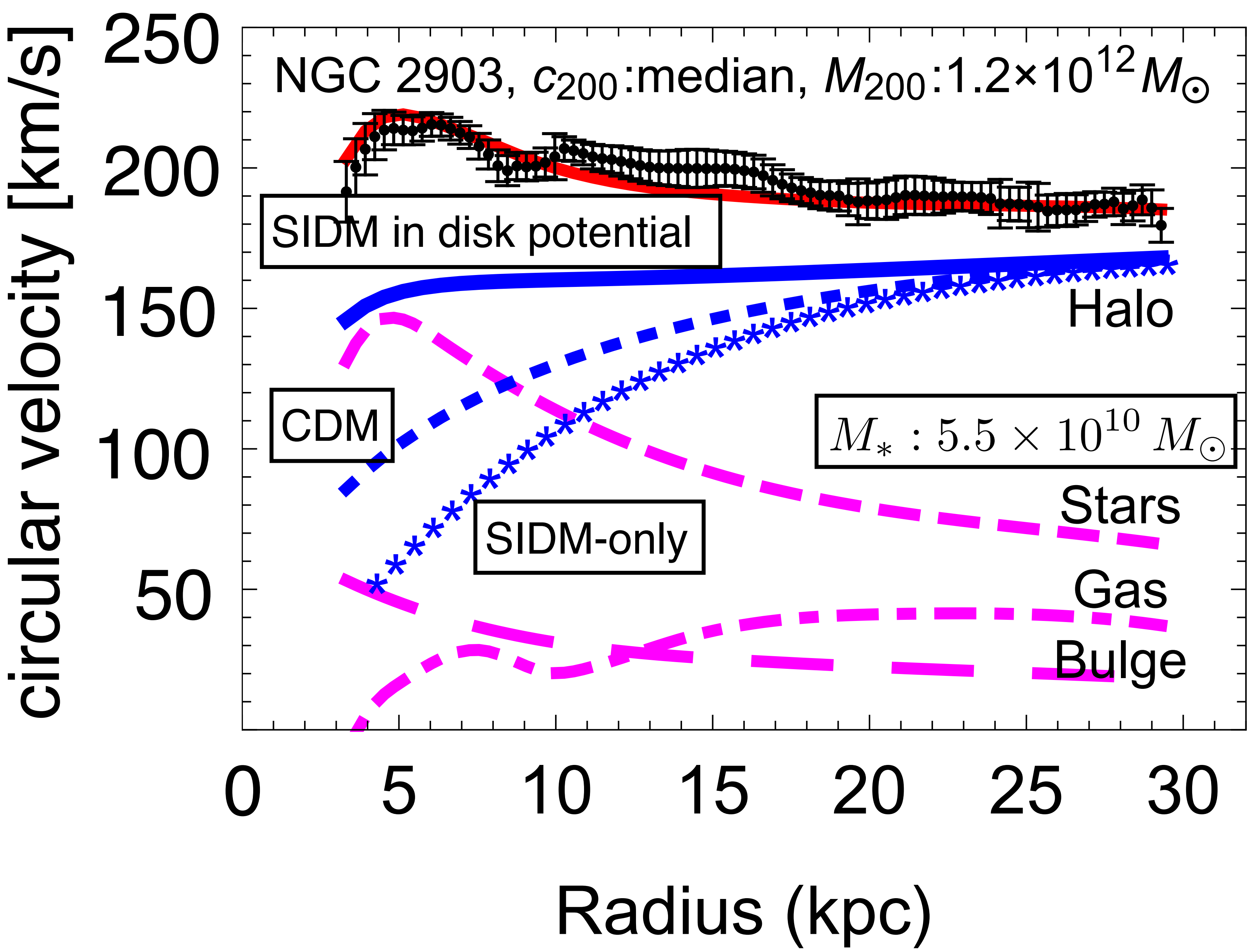
matched to the NFW profile at r_1 ($\sigma v \rho(r_1) t_{age}/m = 1$)



SIDM profile contracts under the presence of compact stellar disk

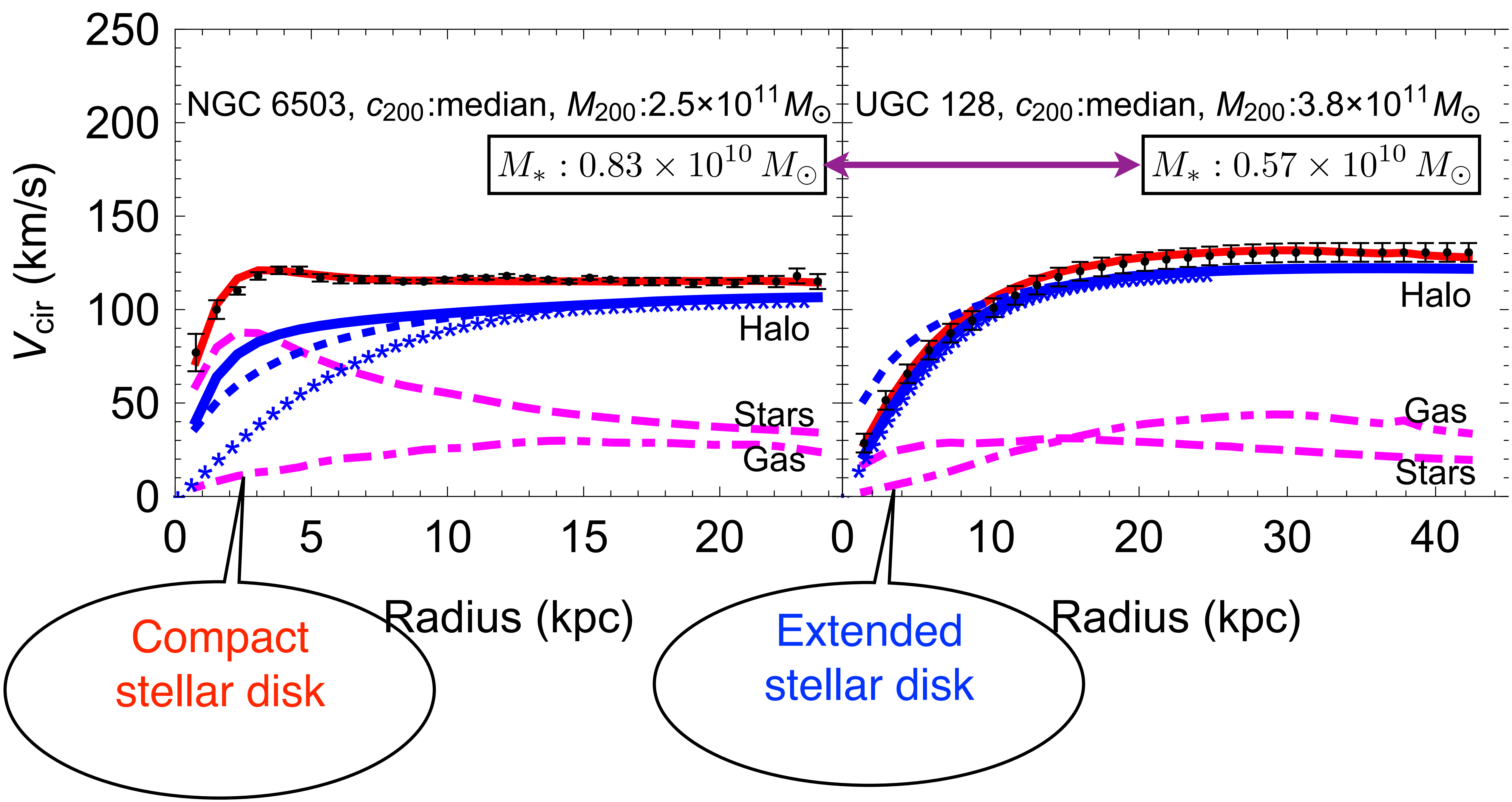
Case study I

In a massive spiral galaxy, the observed compact disk can change the whole SIDM distribution



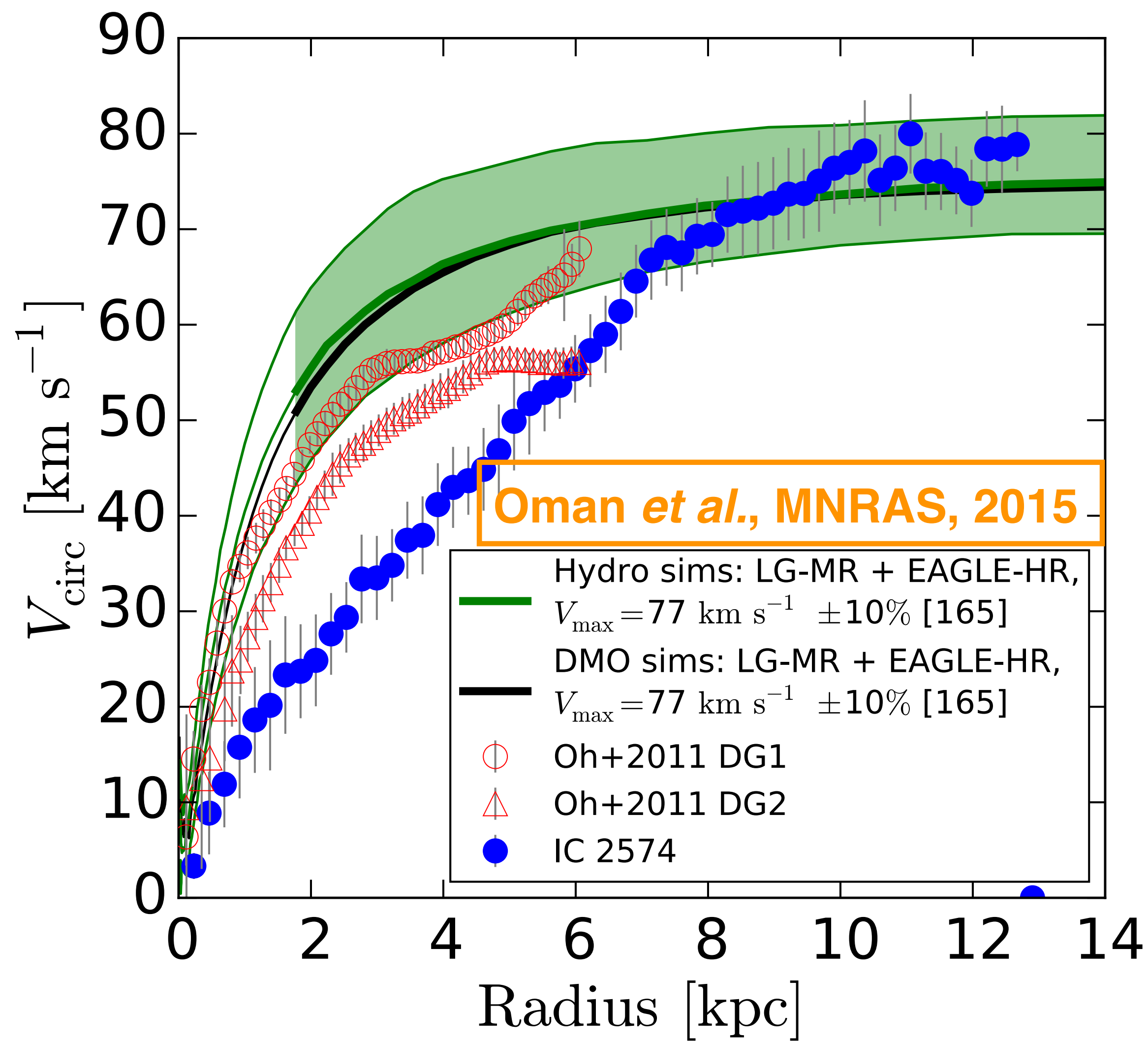
Case study II

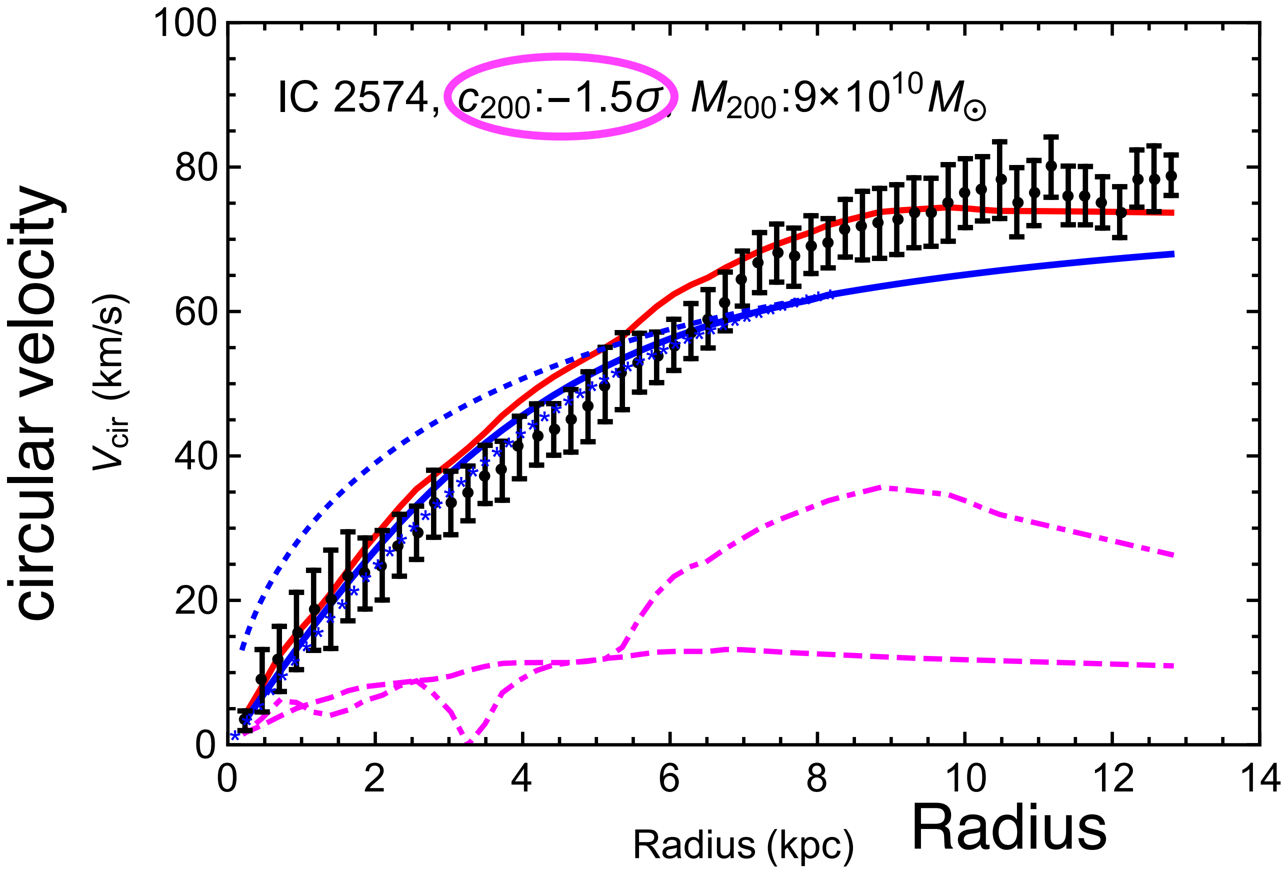
SIDM halo profile reflects how compact the hosted stellar disk is even with similar V_{max} and M_*

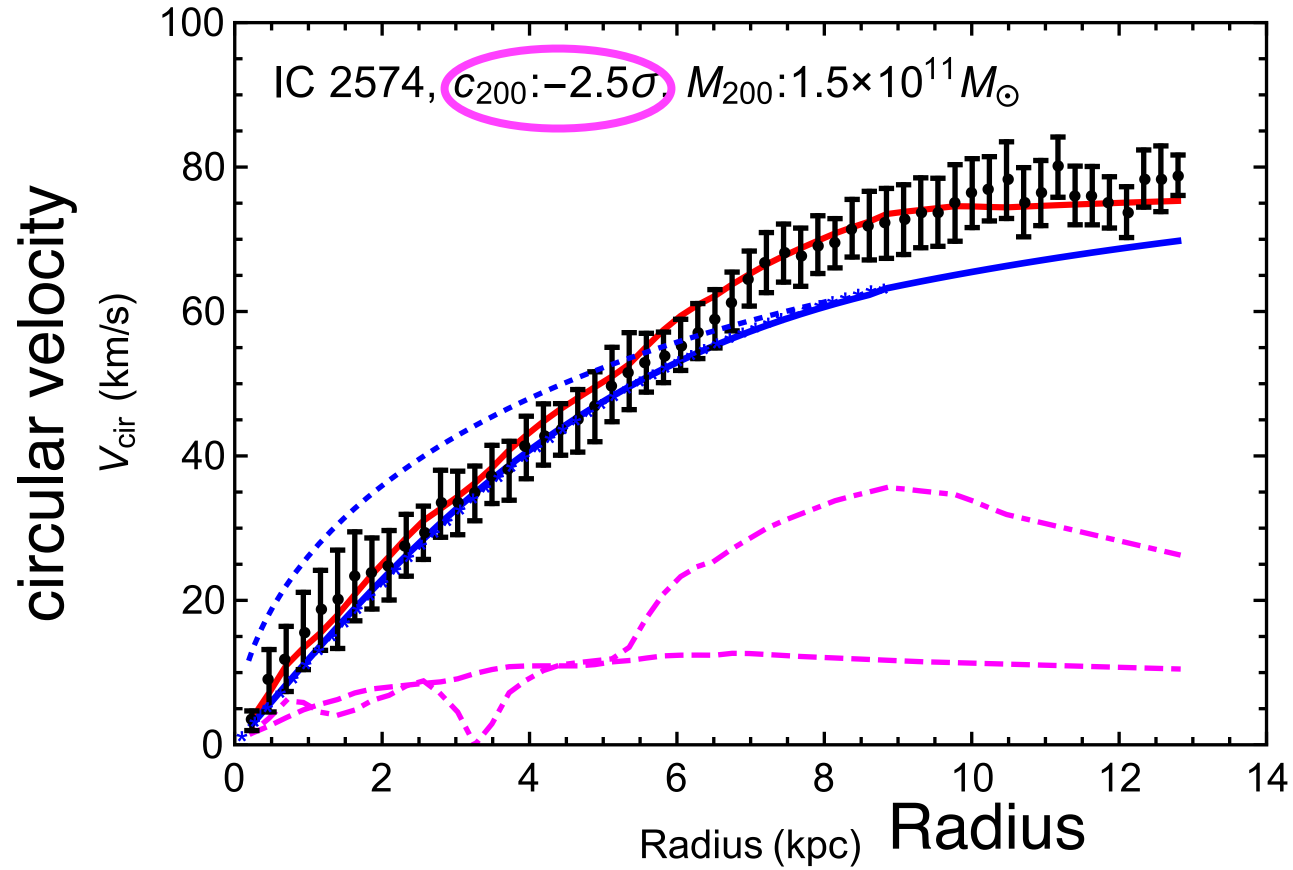


Case study III

The intrinsic scatter of SIDM halos is also needed to reproduce the observed diversity

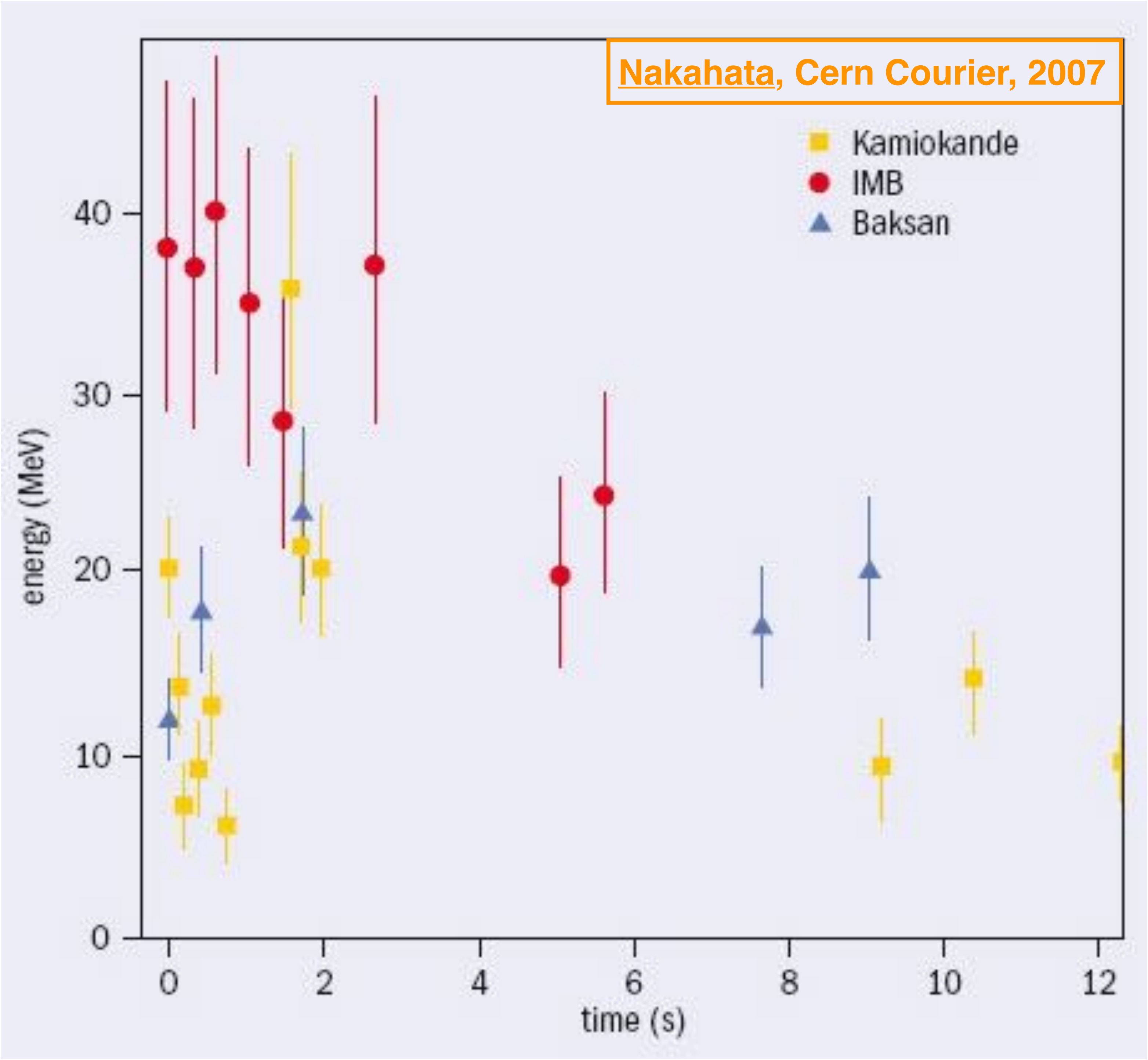




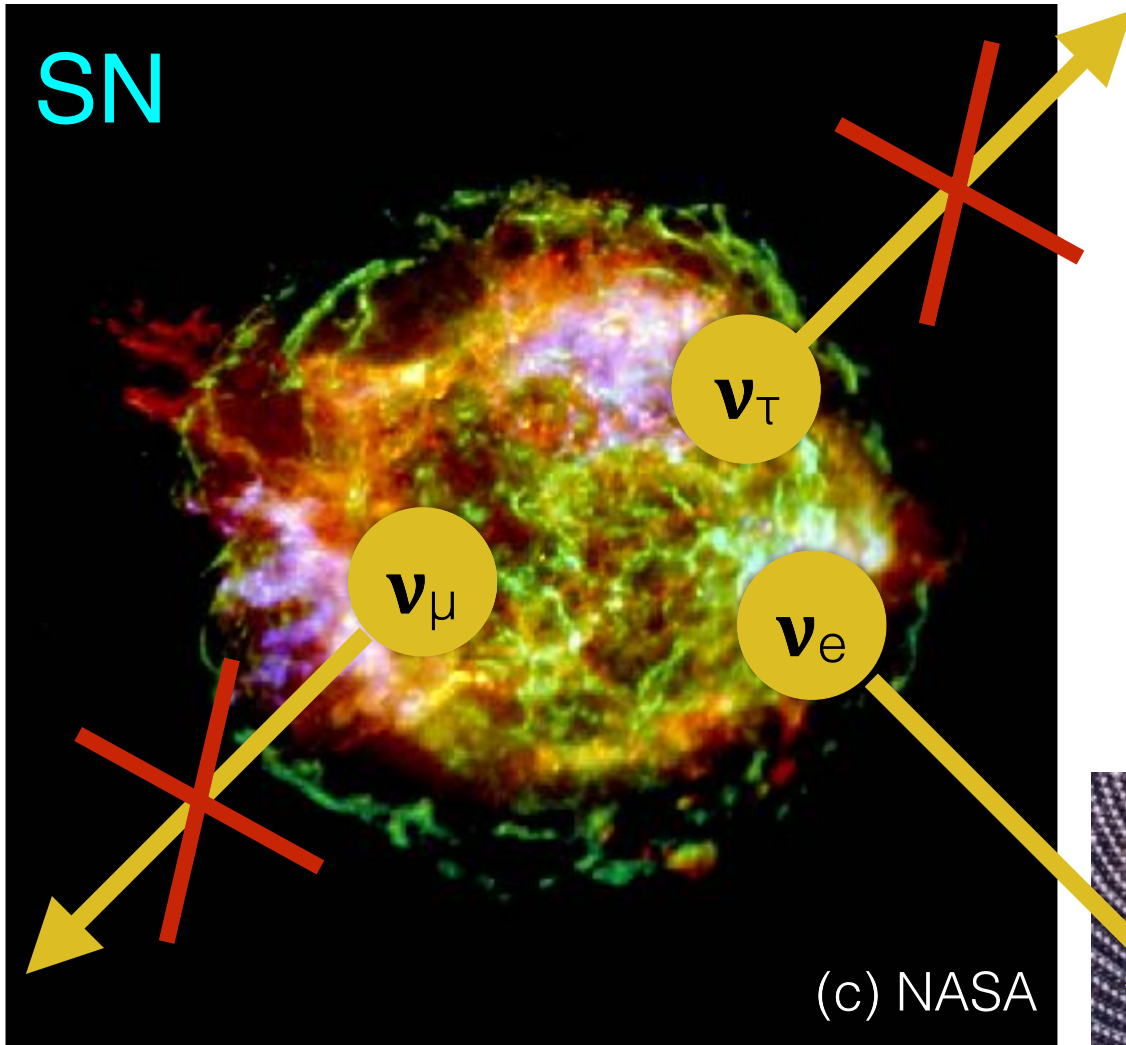


SN 1987A

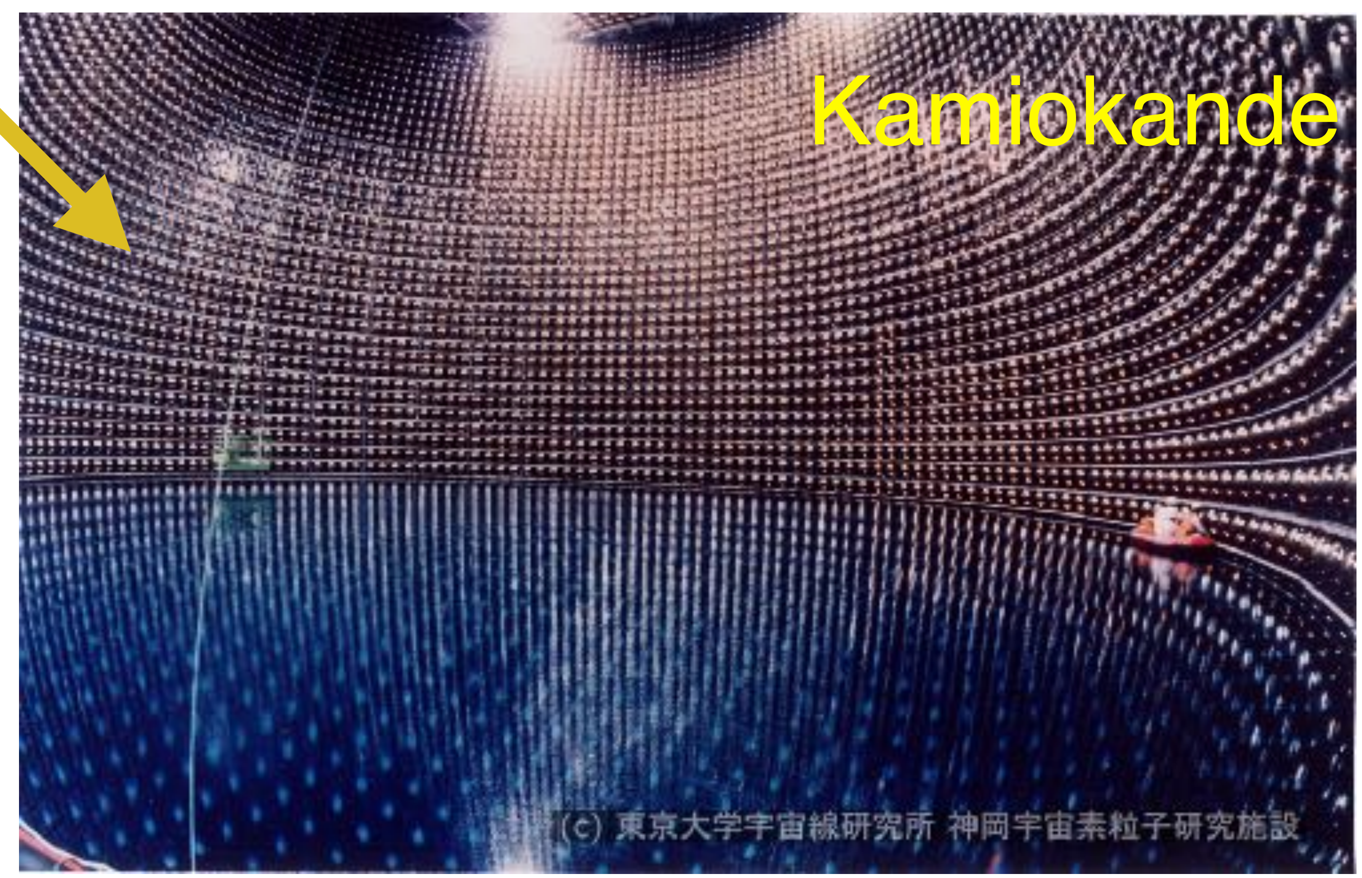
10s determines the duration of neutrino cooling



Summary of astrophysical implications



Only ν_e is emitted from SN



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