# Kinetic decoupling of dark matter: how it affects the relic abundance

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**Mainly based on**
**AK, Hee Jung Kim, Hyungjin Kim, and Sekiguchi, arXiv:1707.09238**

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# Talk Plan

**Part 1**: Particle dark matter
- stability ↔ symmetry

  $Z_2$ symmetry → Weakly Interacting Massive Particle (WIMP)
- relic abundance ↔ production mechanism

  $Z_2$ symmetry → pair annihilation

**Part 2**: Beyond WIMP - a larger symmetry
- Strongly Interacting Massive Particle (SIMP)

  3→2 process

  semi-annihilation

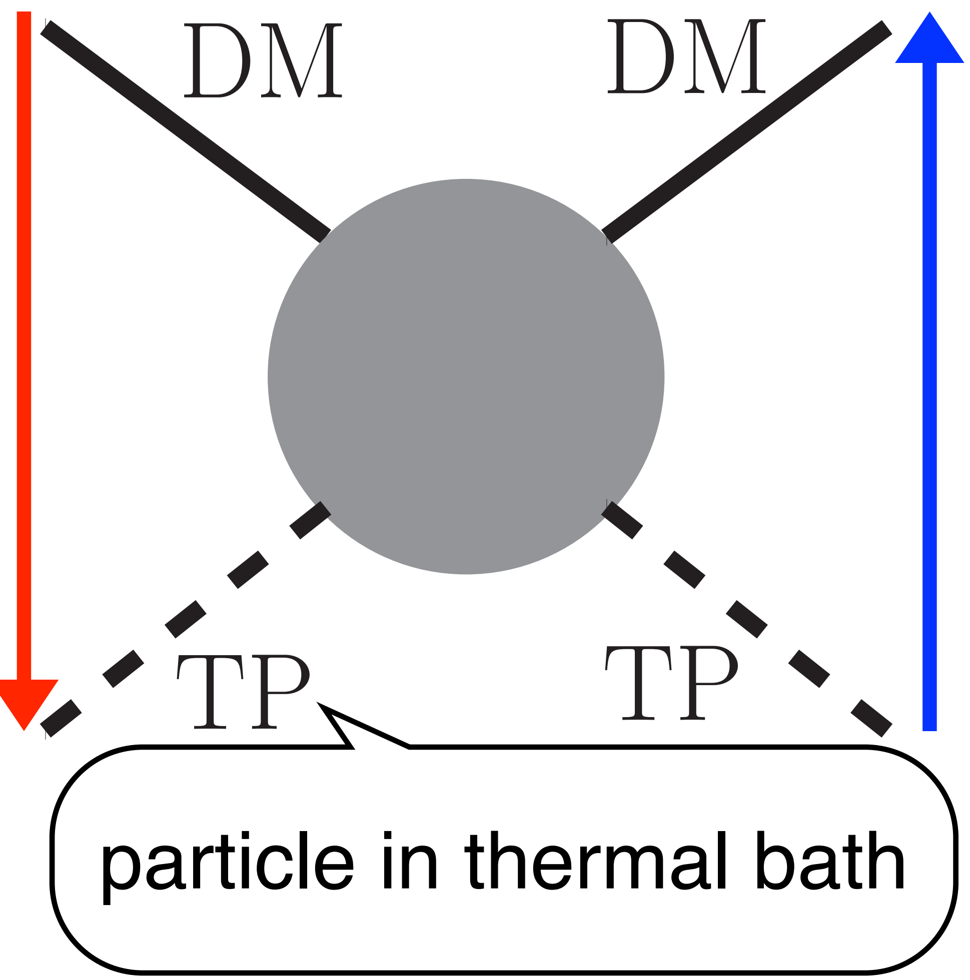
**Part 3**: Impacts of kinetic equilibration on the chemical freeze-out
- co-evolution of the dark matter temperature and number density

**Part 4**: Discussion
- implications for the structure formation of the Universe
- other prospects

# Relic abundance

DM particles should be produced in the early Universe and be left with the **observed relic abundance**

new $Z_2$ symmetry → pair creation & pair annihilation




: **chemical interaction**
- number of DM is changed
- energy & momentum of DM are redistributed

decoupling of chemical interaction
↔ freeze-out of DM number density

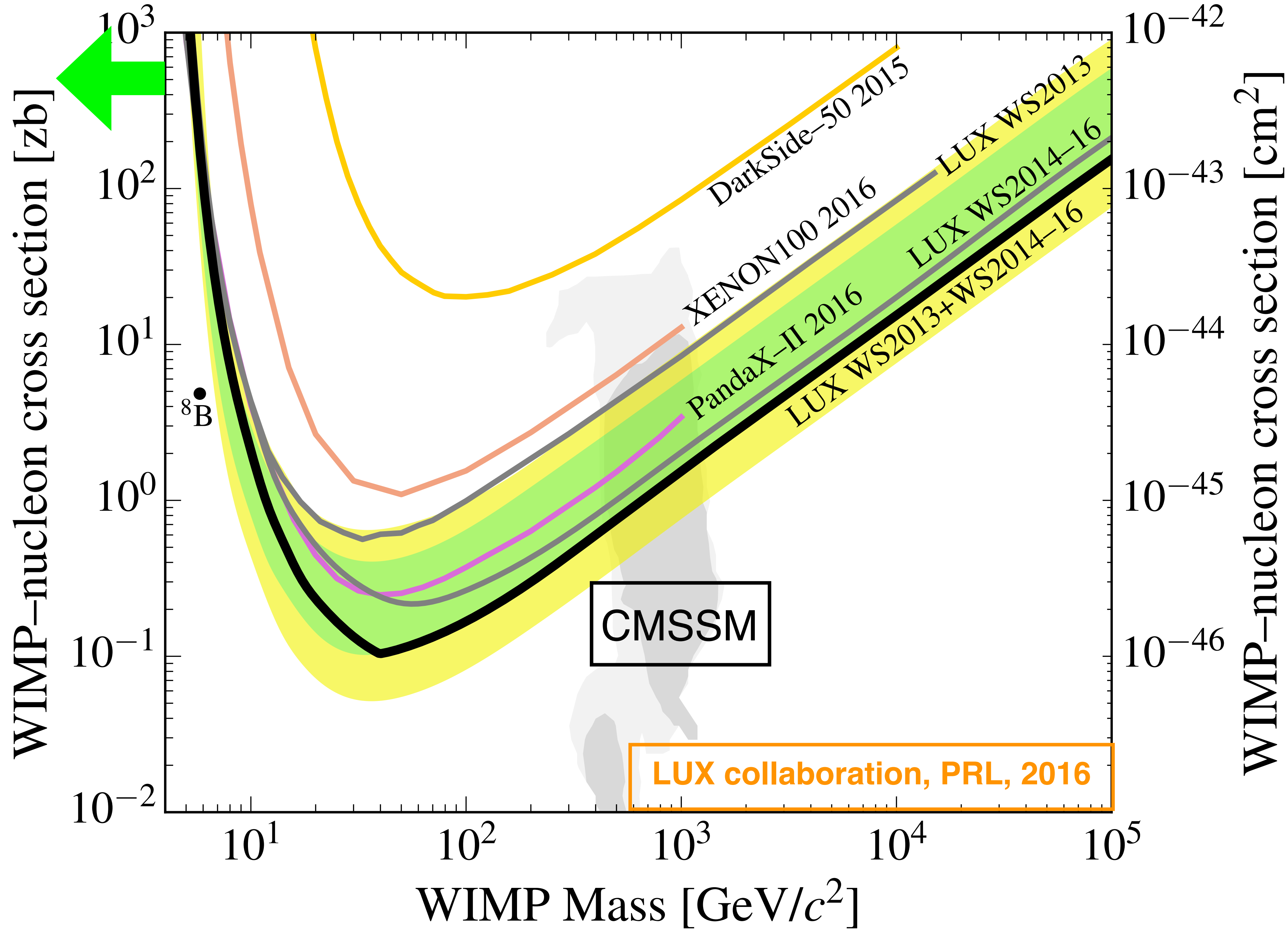
WIMP pair annihilation:

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

$\Omega_\chi h^2 = \Omega_{\rm DM} h^2$
w/ electroweak scale annihilation cross section:
$\langle \sigma_{\rm ann} v_{\rm rel} \rangle \simeq 3 \times 10^{-26}\ {\rm cm}^3/{\rm s}$
→ **Weakly Interacting Massive Particle (WIMP)!!**

# Direct detection

too small recoil energy




SUSY WIMPs have been tightly constrained

# A larger symmetry for the stability

Strongly Interacting Massive Particles (SIMPs)
- **hidden pions** in a hidden confinement sector,
which are described by a non-linear sigma model
w/ an unbroken flavor symmetry: $G/H$

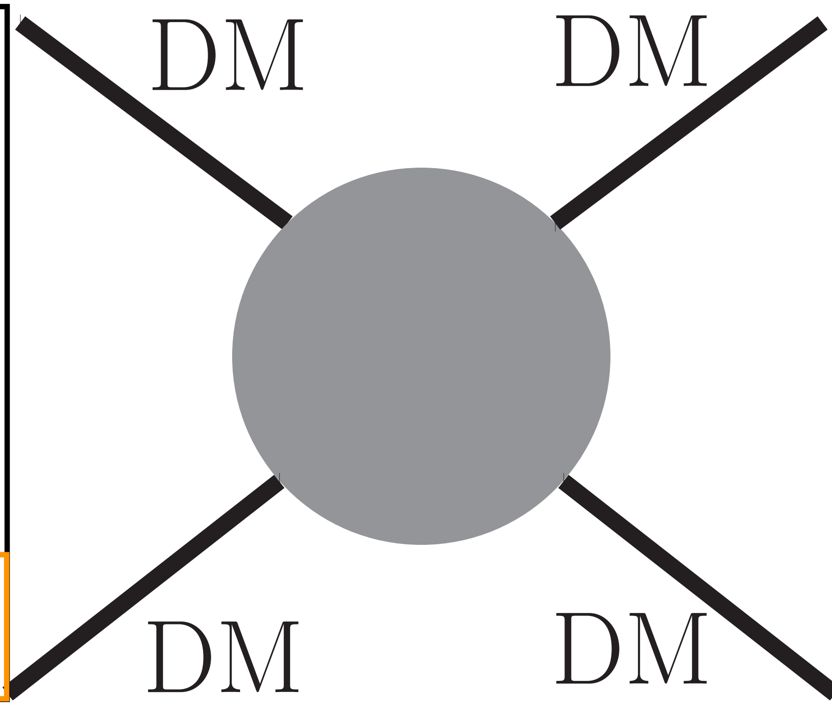
**Hochberg *et al.*, PRL, 2015**

**Unbroken flavor symmetry** → the stability of pions
Two parameters in pion phenomenology -
$m_\pi$: pion mass & $f_\pi$: pion decay constant

**large self-scattering cross section per mass**,
$\sigma_{\rm self}/m_{\rm DM} \sim 0.1\text{–}10\,{\rm cm}^2/{\rm g}$,
may solve **small-scale crisis**: apparent failures of cold dark matter (WIMPs) in reproducing observed sub-galactic scale structure of the Universe

**Spergel *et al.*, PRL, 2000**

**AK, Kaplinghat, Pace, and Yu, arXiv:1611.02716, accepted in PRL**



# SIMP relic density

Wess-Zumino-Witten term → number-changing interaction:

$$\mathcal{L}_{\rm WZW} = \frac{k}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\,{\rm Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right]$$

Wess *et al.*, PLB, 1971

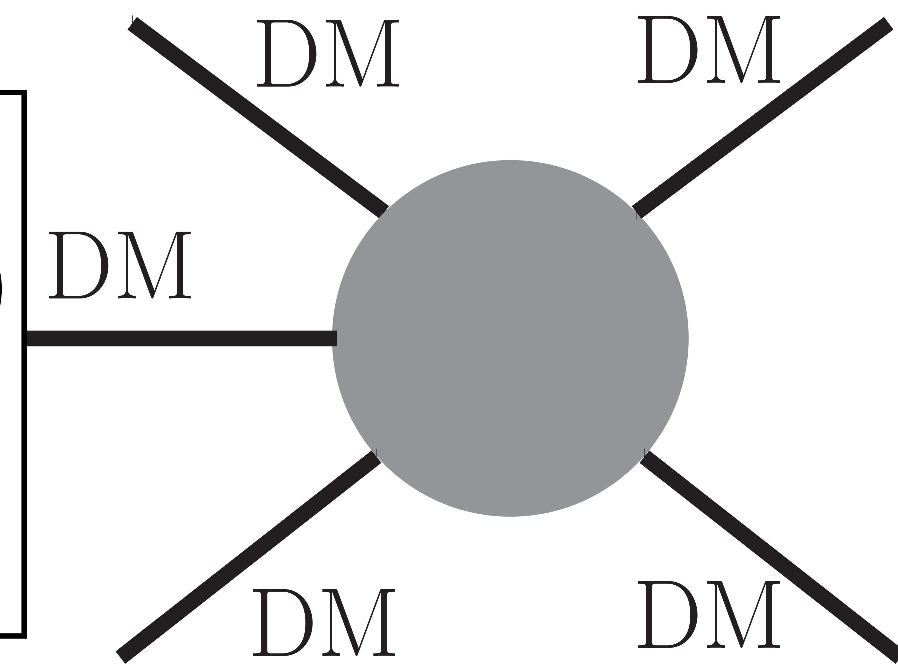
Witten, Nucl. Phys. B, 1983

$k$ - reproduce the quantum anomaly of $G$ in the ultraviolet theory (quarks): $k = 2N_c$ in a QCD-like theory

**3→2 process**:

$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = -\langle\sigma_{3\to 2}v_{\rm rel}^2\rangle\left(n_{\rm DM}^3 - n_{\rm DM}^2 n_{\rm DM}^{\rm eq}\right)$$

$\langle\sigma_{3\to 2}v_{\rm rel}^2\rangle \sim \frac{m_\pi^5}{f_\pi^{10}}$ : generalized cross section w/ mass dimension -5




$\Omega_\pi h^2 = \Omega_{\rm DM}h^2$ & $\sigma_{\rm self}/m_{\rm DM} \sim 0.1\text{–}10\,{\rm cm}^2/{\rm g}$
w/ $m_\pi \sim f_\pi \sim 0.1\text{–}1\,{\rm GeV}$

# Semi-annihilation to an axion-like particle (ALP)

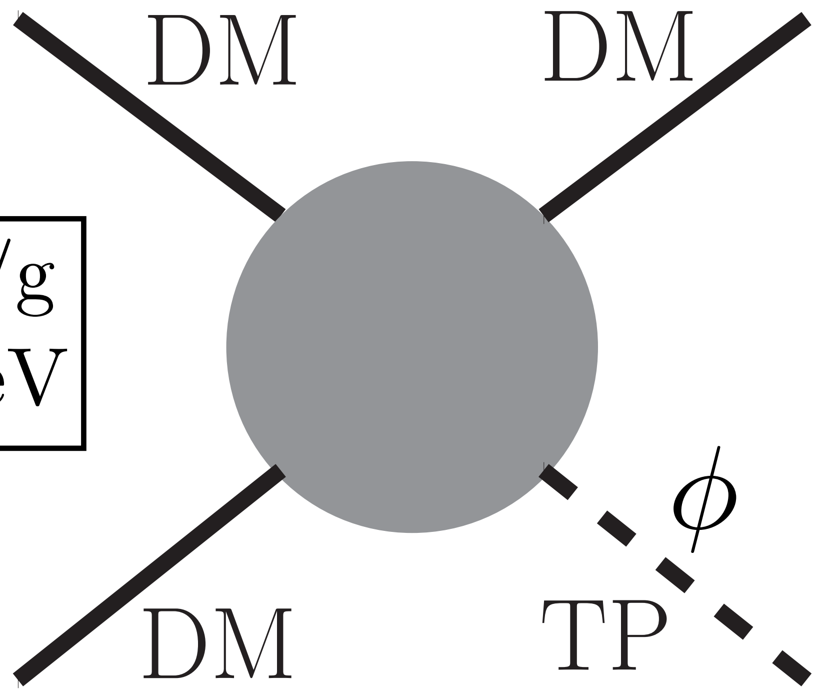
pion-ALP mixing through the anomalous coupling:

$$\frac{g_H^2}{32\pi^2}\left(\frac{\phi}{f}+\theta_H\right)H^i{}_{\mu\nu}\widetilde{H}^{i\mu\nu}$$

AK, Hyungjin Kim, and Sekiguchi, PRD, 2017

**semi-annihilation**:

$$\dot{n}_{\rm DM}+3Hn_{\rm DM}=-\frac{1}{2}\langle\sigma_{\rm semi}v_{\rm rel}\rangle(n_{\rm DM}^2-n_{\rm DM}n_{\rm DM}^{\rm eq})$$




→ $\Omega_\pi h^2=\Omega_{\rm DM}h^2$ & $\sigma_{\rm self}/m_{\rm DM}\sim 0.1$–$10\,{\rm cm}^2/{\rm g}$
w/ $f_\pi > m_\pi \sim 0.1$–$1\,{\rm GeV}$ & $f\sim 100$–$1000\,{\rm GeV}$

improving the perturbativity of the non-linear sigma model:
$m_\pi\simeq\Lambda_{\rm cut}\to m_\pi<\Lambda_{\rm cut}$
where $\Lambda_{\rm cut}\simeq 2\pi f_\pi/\sqrt{N_c}$ from the naïve dimensional analysis

Manohar *et al.*, Nucl. Phys. B, 1984

# Assumption in Boltzmann equations

WIMP pair annihilation:

pair annihilation

pair creation

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

Hubble expansion rate

thermally averaged annihilation cross section

(non-relativistic) equilibrium number density with # of spin d.o.f being g:

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

SIMP 3→2 process:

$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = -\langle \sigma_{3\to 2} v_{\rm rel}^2\rangle \left(n_{\rm DM}^3 - n_{\rm DM}^2 n_{\rm DM}^{\rm eq}\right)$$

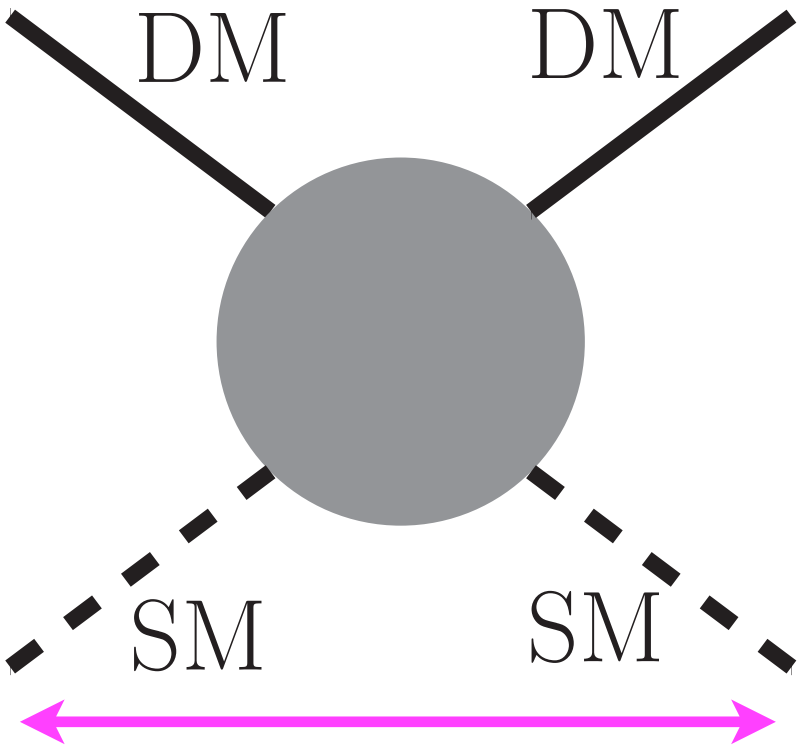
semi-annihilation:

$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = -\frac{1}{2}\langle \sigma_{\rm semi} v_{\rm rel}\rangle \left(n_{\rm DM}^2 - n_{\rm DM} n_{\rm DM}^{\rm eq}\right)$$

**WHOSE temperature is $T$ ?**

kinetic equilibrium $\leftrightarrow$ $T_{\rm DM} = T \propto 1/a$

# Kinetic interaction of WIMPs




: kinetic interaction
- DM number is conserved
- DM energy & momentum are redistributed

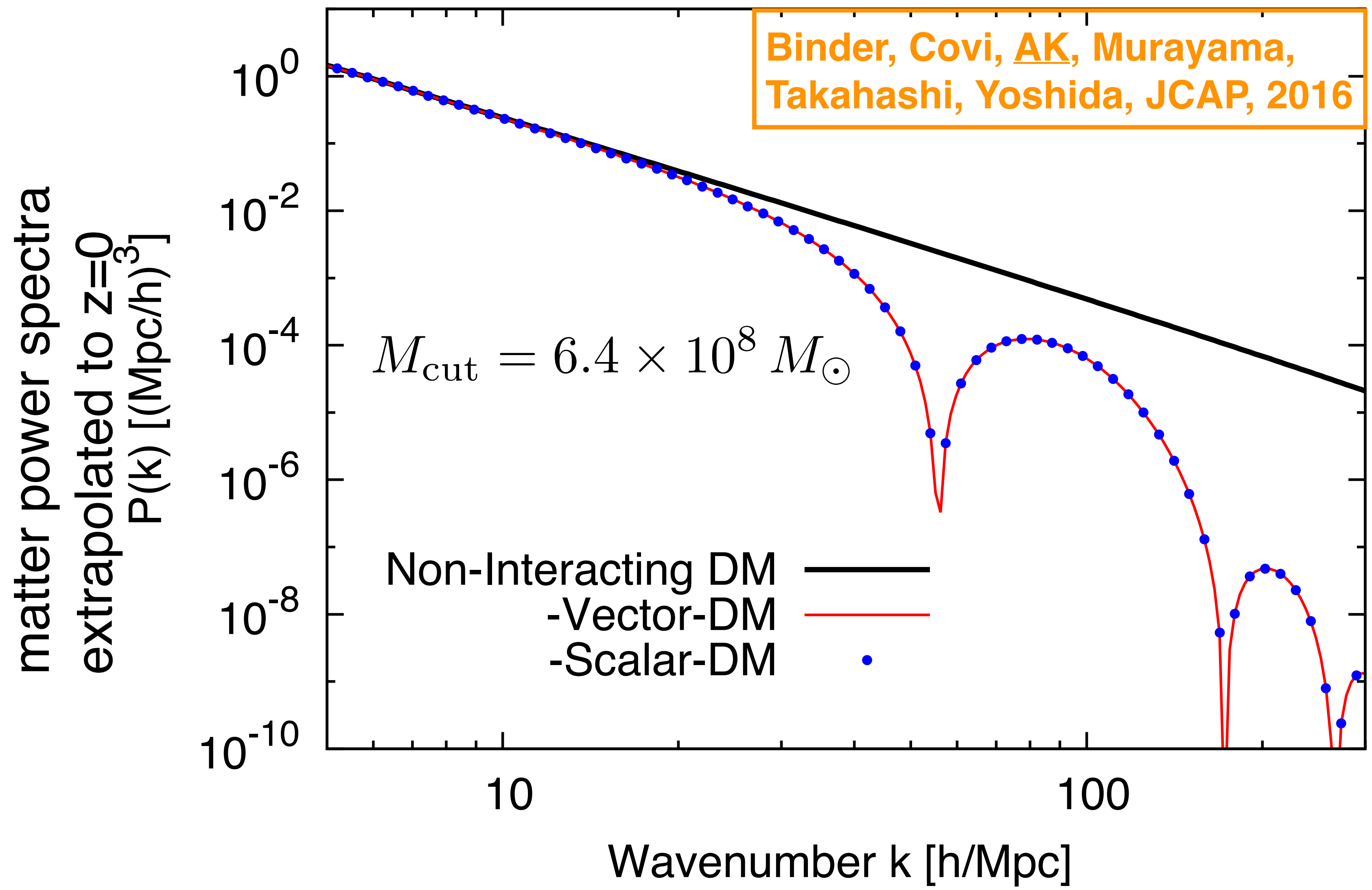
→ decoupling of kinetic interaction $\leftrightarrow T_{\rm DM} \propto 1/a \rightarrow T_{\rm DM} \propto 1/a^2$

→ minimum mass of protohalo

**crossing symmetry**
kinetic interaction
↔ chemical interaction

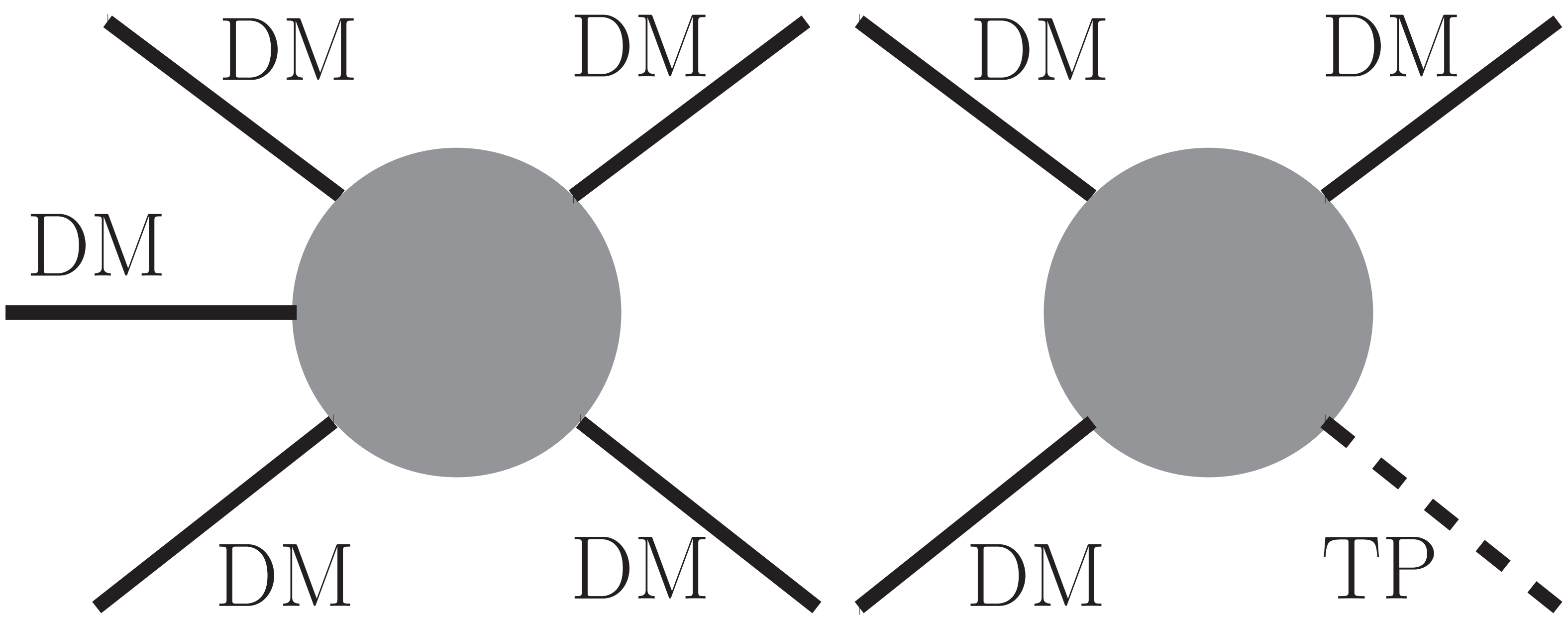
exception:

Binder *et al.*, arXiv:1706.07433
Gustafsson's talk!



# Importance of SIMP kinetic interaction

**WHAT** guarantees $T_{\rm DM} = T \propto 1/a$ ?




number-changing interactions have **nothing to do with** kinetic equilibration

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

Carlson *et al.*, APJ, 1992

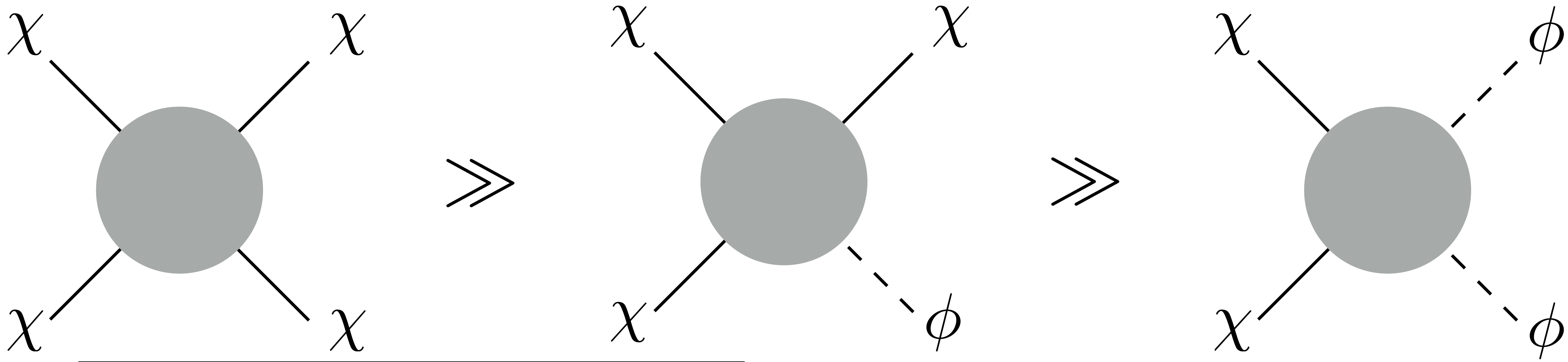
**solely w/** 3→2 process ↔ **isolated** DM fluid

→ $T_{\rm DM} \propto 1/\ln a$ (from comoving entropy density conservation)
& $n_{\rm DM}/s \propto 1/\ln a$ until the decoupling of 3→2 process

**Elastic scattering** of SIMPs with the SM particles
→ the relic density of dark matter!!

Kuflik *et al.*, PRL, 2016

# Freeze-out driven by the semi-annihilation




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

AK, Hee Jung Kim, Hyungjin Kim, and Sekiguchi, arXiv:1707.09238

co-evolution equations:

adiabatic cooling

$$\frac{d}{dx}Y_\chi = -\frac{\lambda}{x^2}Y_\chi\left[Y_\chi - Y_\chi^{\rm eq}(x_\chi)\mathcal{J}(x_\chi, x)\right]$$

$$\sigma^2_{E_\chi/m_\chi}\frac{d}{dx}x_\chi = \frac{3}{x}\frac{1}{x_\chi} + \frac{\bar\lambda}{x^2}\left[Y_\chi - Y_\chi^{\rm eq}(x_\chi)\mathcal{K}(x_\chi, x)\right]$$

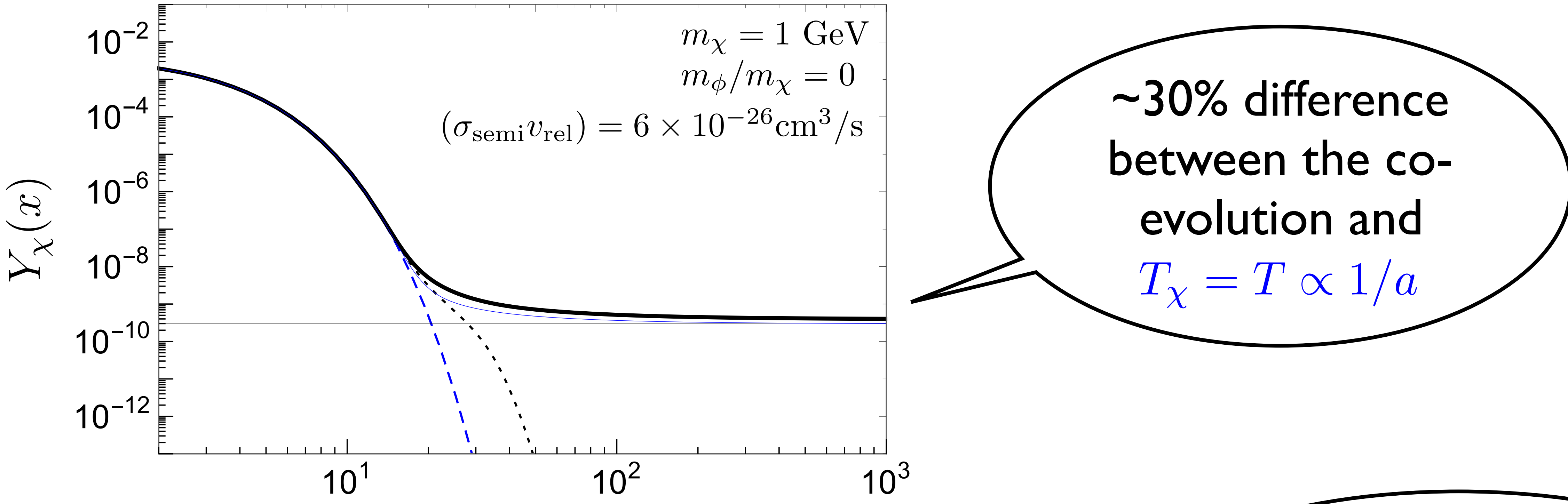
heating through the semi-annihilation

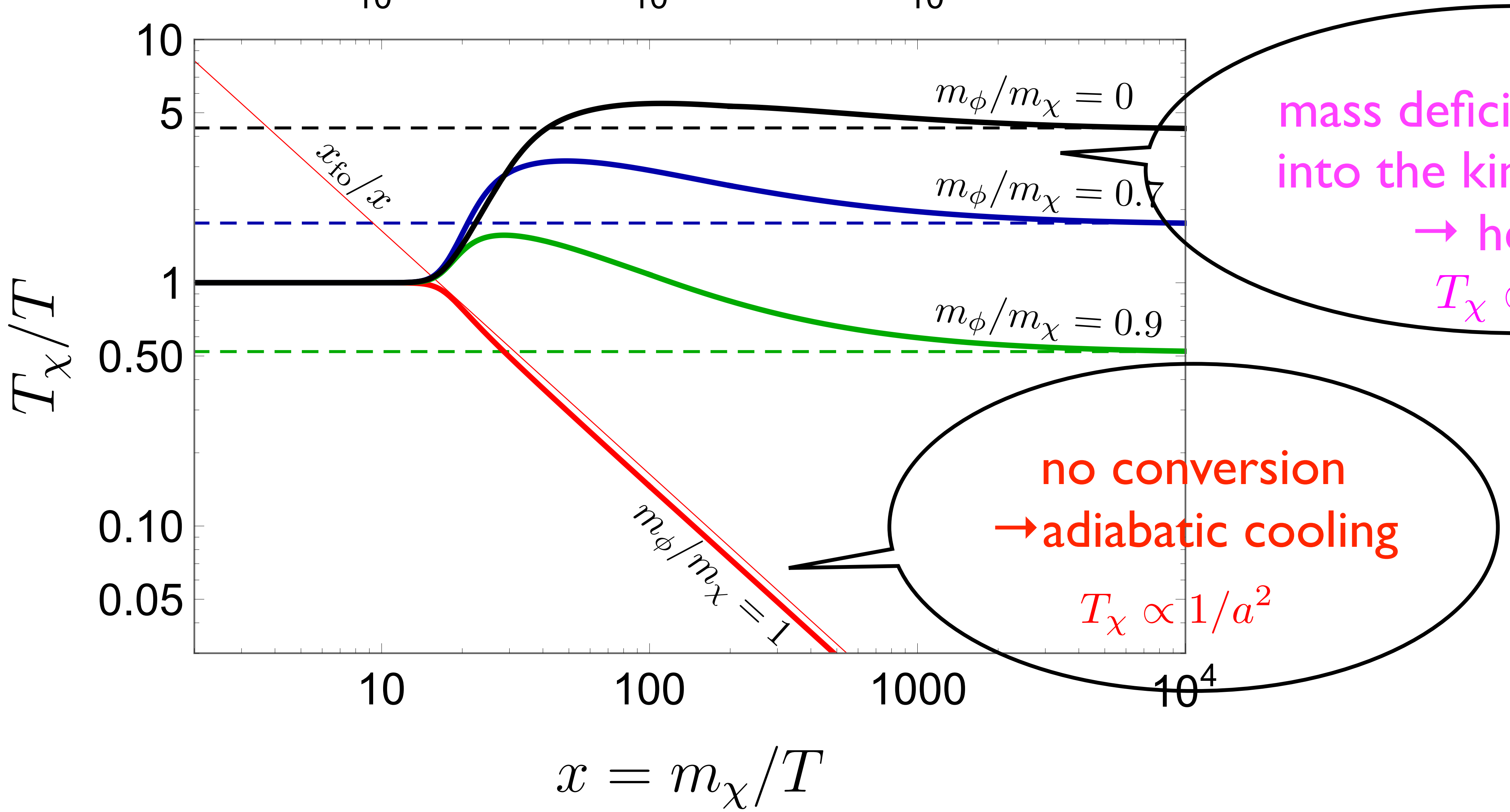
$$\lambda = \frac{xs\langle\sigma_{\rm semi}v_{\rm rel}\rangle_{T_\chi,T_\chi}}{2H}, \quad \mathcal{J}(x_\chi, x) = \frac{n_\phi^{\rm eq}(T_\phi = T)}{n_\phi^{\rm eq}(T_\phi = T_\chi)}\frac{\langle\sigma_{\rm inv}v_{\rm rel}\rangle_{T_\chi,T_\phi=T}}{\langle\sigma_{\rm inv}v_{\rm rel}\rangle_{T_\chi,T_\phi=T_\chi}}$$

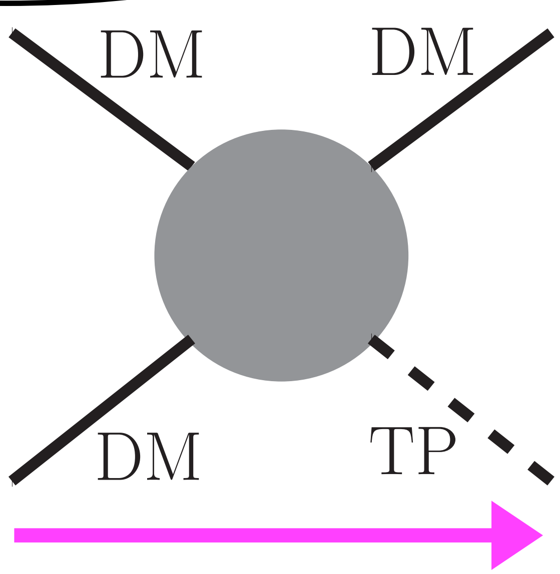
$$\bar\lambda = \frac{xs\langle(\Delta E/m_\chi)\sigma_{\rm inv}v_{\rm rel}\rangle_{T_\chi,T_\phi=T_\chi}}{H}\frac{n_\phi^{\rm eq}(T_\phi = T_\chi)}{n_\chi^{\rm eq}(T_\chi)}, \quad \mathcal{K}(x_\chi, x) \equiv \frac{n_\phi^{\rm eq}(T_\phi = T)}{n_\phi^{\rm eq}(T_\phi = T_\chi)}\frac{\langle\Delta E\,\sigma_{\rm inv}v_{\rm rel}\rangle_{T_\chi,T_\phi=T}}{\langle\Delta E\,\sigma_{\rm inv}v_{\rm rel}\rangle_{T_\chi,T_\phi=T_\chi}}$$

$$\sigma^2_{E_\chi/m_\chi} = \langle E_\chi^2/m_\chi^2\rangle_{T_\chi} - \langle E_\chi/m_\chi\rangle^2_{T_\chi}, \quad \Delta E = E_\phi - \langle E_\chi\rangle_{T_\chi}$$

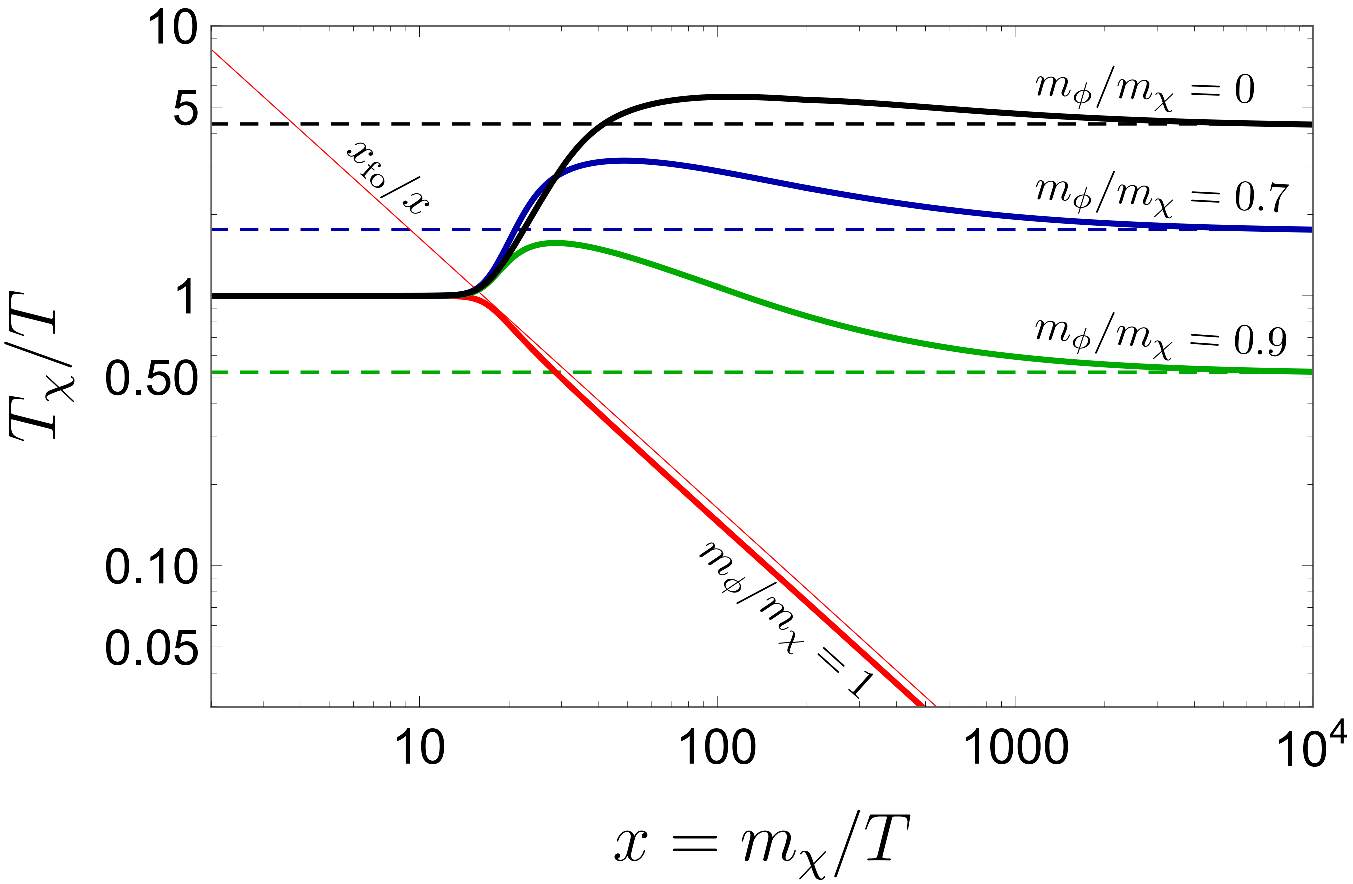
# Co-evolution of the temperature and number density



# Warmness




Jeans scale at the matter-radiation equality:

$$k_{\rm J} = a\sqrt{\frac{4\pi G\rho_{\rm m}}{\langle\vec{v}^2\rangle}}\Bigg|_{a=a_{\rm eq}}$$

**AK, Yoshida, Kohri, and Takahashi, JCAP, 2013**

early decoupled warm dark matter:

$$k_{\rm J} = 210\,{\rm Mpc}^{-1}\left(\frac{m_{\rm WDM}}{6\,{\rm keV}}\right)^{4/3}$$

Ly-α constraint: $m_{\rm WDM} > 5.3\,{\rm keV}$

**Baur *et al.*, arXiv:1706.03118**

for $m_\phi = m_\chi$ ,

$$k_{\rm J} = 2\times10^6\,{\rm Mpc}^{-1}\left(\frac{m_\chi}{1\,{\rm GeV}}\right)^{1/2}\left(\frac{T_{\rm fo}}{50\,{\rm GeV}}\right)^{1/2}$$

GeV mass warm dark matter!!

self-scattering → sharing the mass deficit w/ others

for $m_\phi \ll m_\chi$,

$$k_{\rm J} \simeq 220\,{\rm Mpc}^{-1}\left(\frac{m_\chi}{1\,{\rm GeV}}\right)^{1/2}\left(\frac{T_{\rm self}}{T_{\rm eq}}\right)^{1/2}\left(\frac{T_\chi}{T}\right)^{-1/2}_{\rm asy}$$

# Summary

Minimal $Z_2$ symmetry to stabilize particle DM → WIMPs
Hidden flavor symmetry stabilizes hidden pions (SIMPs)

Sub-GeV pion mass and comparable pion decay constant/ electroweak scale ALP decay constant
→ correct relic abundance through the 3→2 process/semi-annihilation and large cross section to produce sizable halo cores

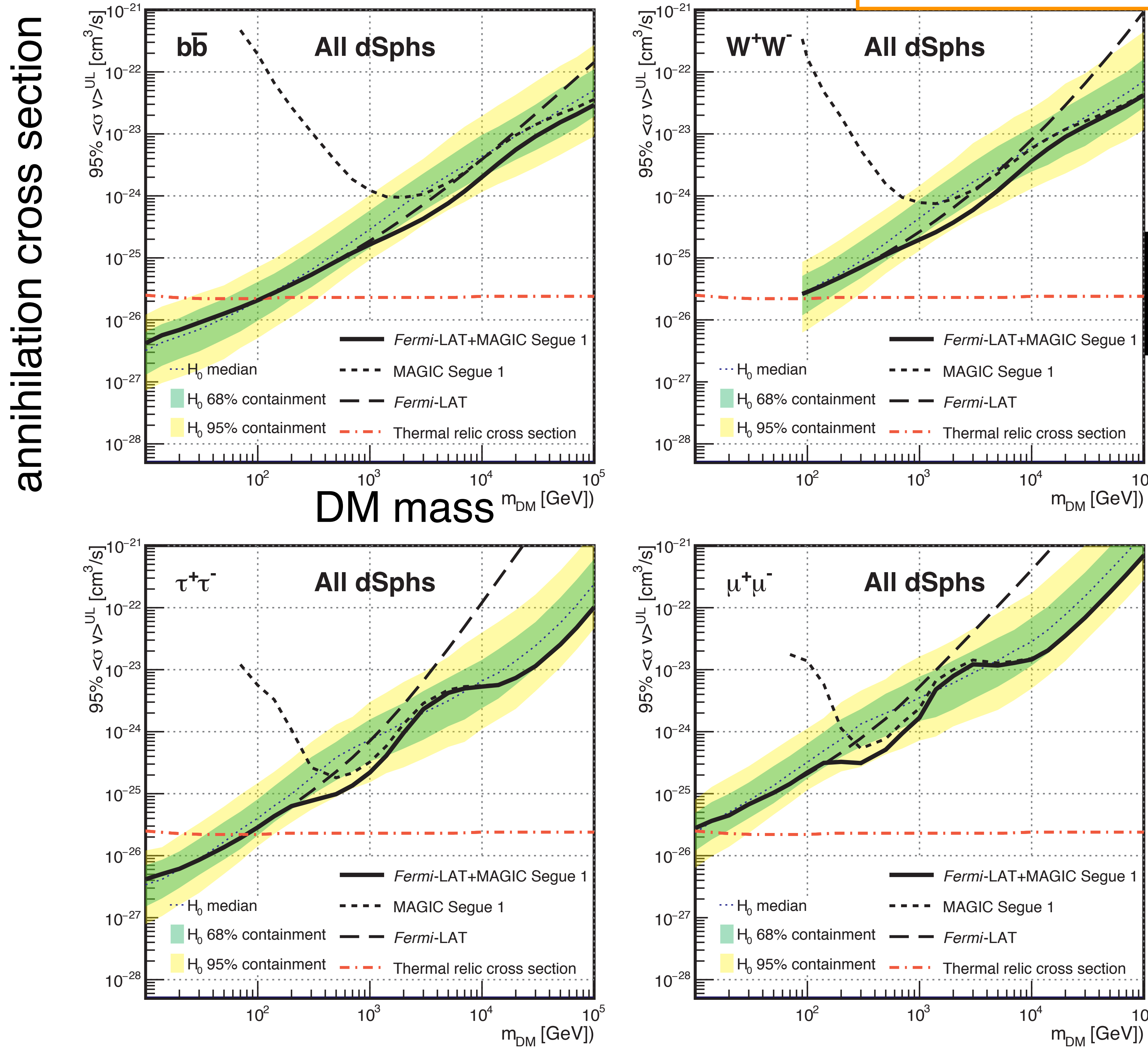
Kinetic equilibration has nothing to do with number-changing reactions in SIMPs unlike WIMPs

Semi-annihilating SIMPs
w/o elastic scatterings with SM particles
→ co-evolution of the DM temperature and number density
$T_{\rm DM} \propto 1/a$ after the freeze-out due to the heating though the semi-annihilation

# Thank you for your attention

# Indirect detection

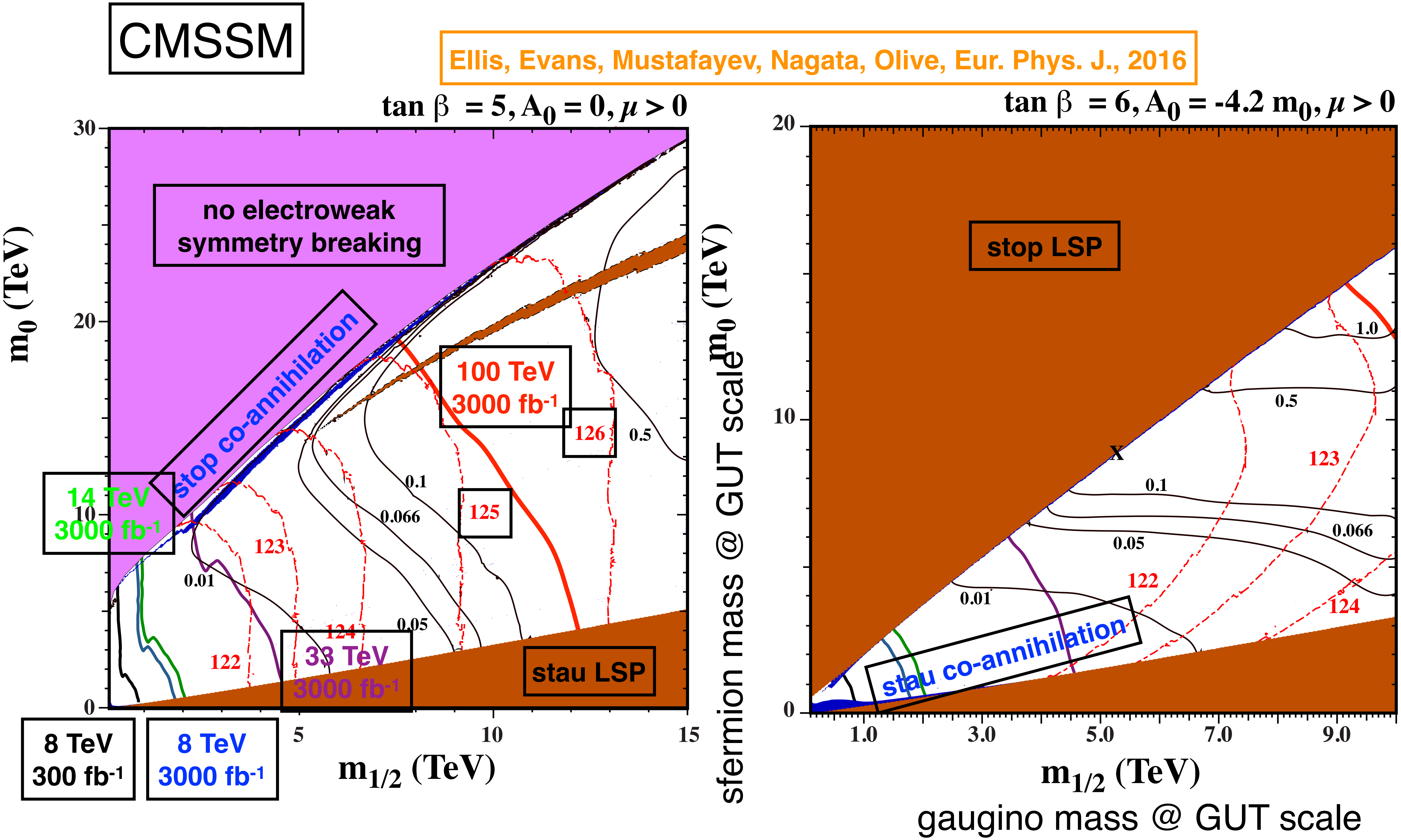
Magic and Fermi-LAT Collaborations, JCAP, 2016




**canonical cross section ↔ thermal relic**

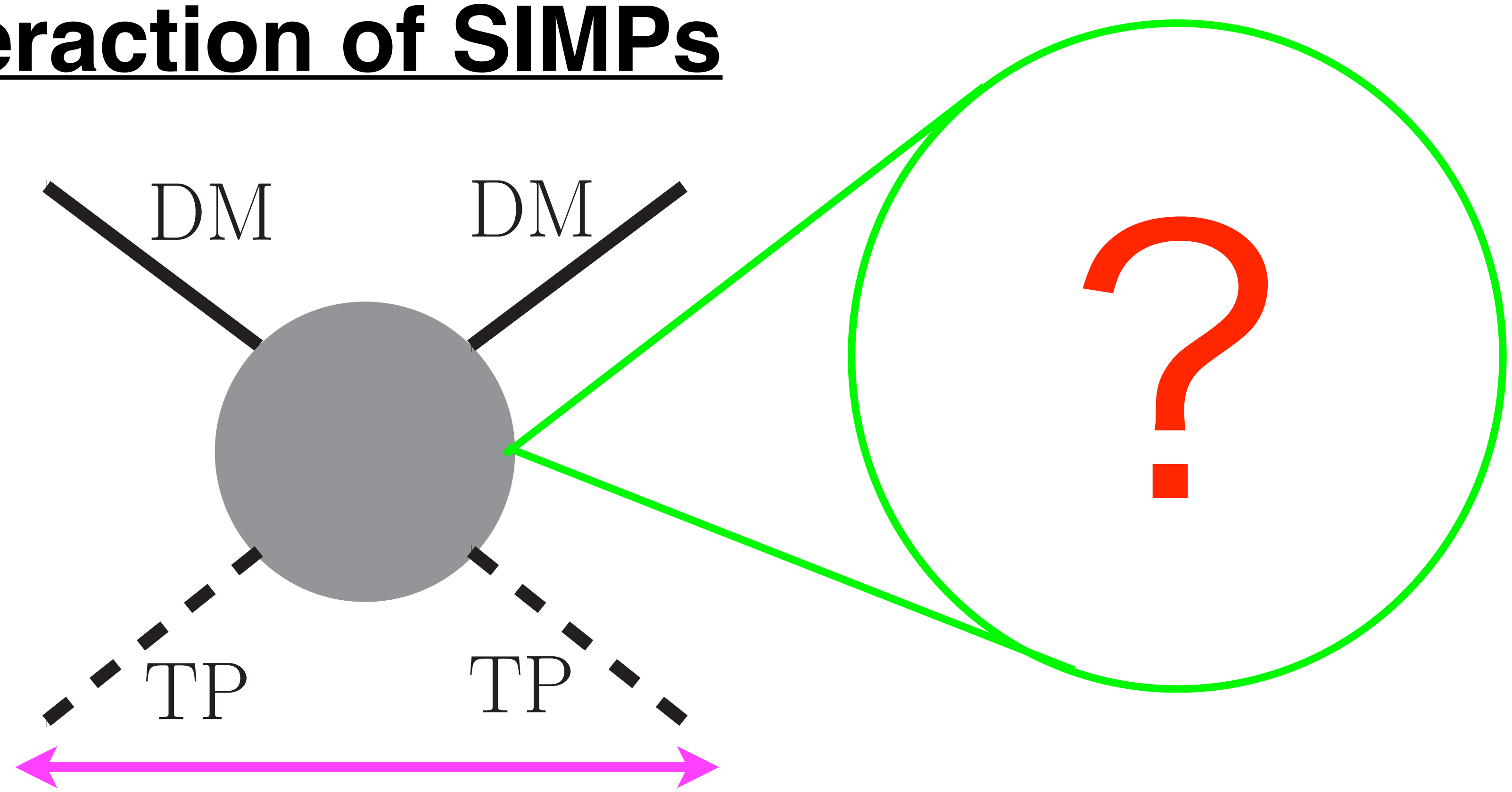
The thermal WIMP mass has been bounded from below:
$m_{\rm DM} \gtrsim 100\,{\rm GeV}$

# Collider experiment




The sparticle masses have been pushed up to $\sim 10\,\mathrm{TeV}$
→ look for a new paradigm?

# Kinetic interaction of SIMPs




**Possible kinetic interactions (portals)**

Kinetic mixing portal: gauging abelian part of the unbroken symmetry

Lee *et al.*, PLB, 2015 | Hochberg *et al.*, JHEP, 2016

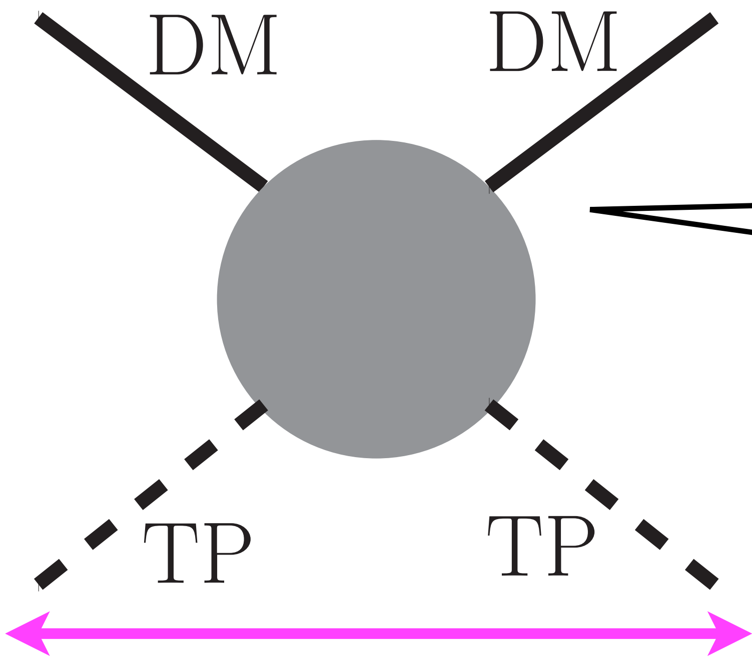
Higgs portal: introducing a hidden Higgs, VEV of which provides a mass to quarks (and pions)

AK, Yamada, Yanagida, and Yonekura, PRD, 2016

Axion-like particle (ALP) portal: introducing an axion-like particle, which has anomalous couplings both to a SM gauge field and to the hidden gauge field

AK, Hyungjin Kim, and Sekiguchi, PRD, 2017

# Higgs portal




Two suppressions:
the mixing angle ($\theta \sim v_h v_s / m_h^2$)
and the Yukawa coupling.
Remark that even muons are barely available during the pion freeze-out

Off-shell exchange of the hidden Higgs ( $s$ ) → not sufficiently rapid to keep the DM pions in kinetic equilibrium with the SM plasma

The decay and inverse decay of the hidden Higgs keeps it in thermal equilibrium →
Thermalized hidden Higgses: $\pi s \to \pi s$ elastic scattering
→ the kinetic equilibration of the pions with the SM plasma

# Hidden sector in an ALP model

Lagrangian density w/ $G = \mathrm{SU}(N_f)_L \times \mathrm{SU}(N_f)_R$ and $H = \mathrm{SU}(N_f)_V$:

$$\mathcal{L}_{\rm hid} = \mathcal{L}_0 + \mathcal{L}_{\rm CP} + \mathcal{L}_{\rm CPV} + \mathcal{L}_{\rm WZW}$$

$$\mathcal{L}_0 = \frac{1}{2}\left(\partial_\mu \pi^a\right)^2 + \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \frac{1}{2} m_\pi^2 \left(\pi^a\right)^2 - \frac{1}{2} m_\phi^2 \phi^2$$

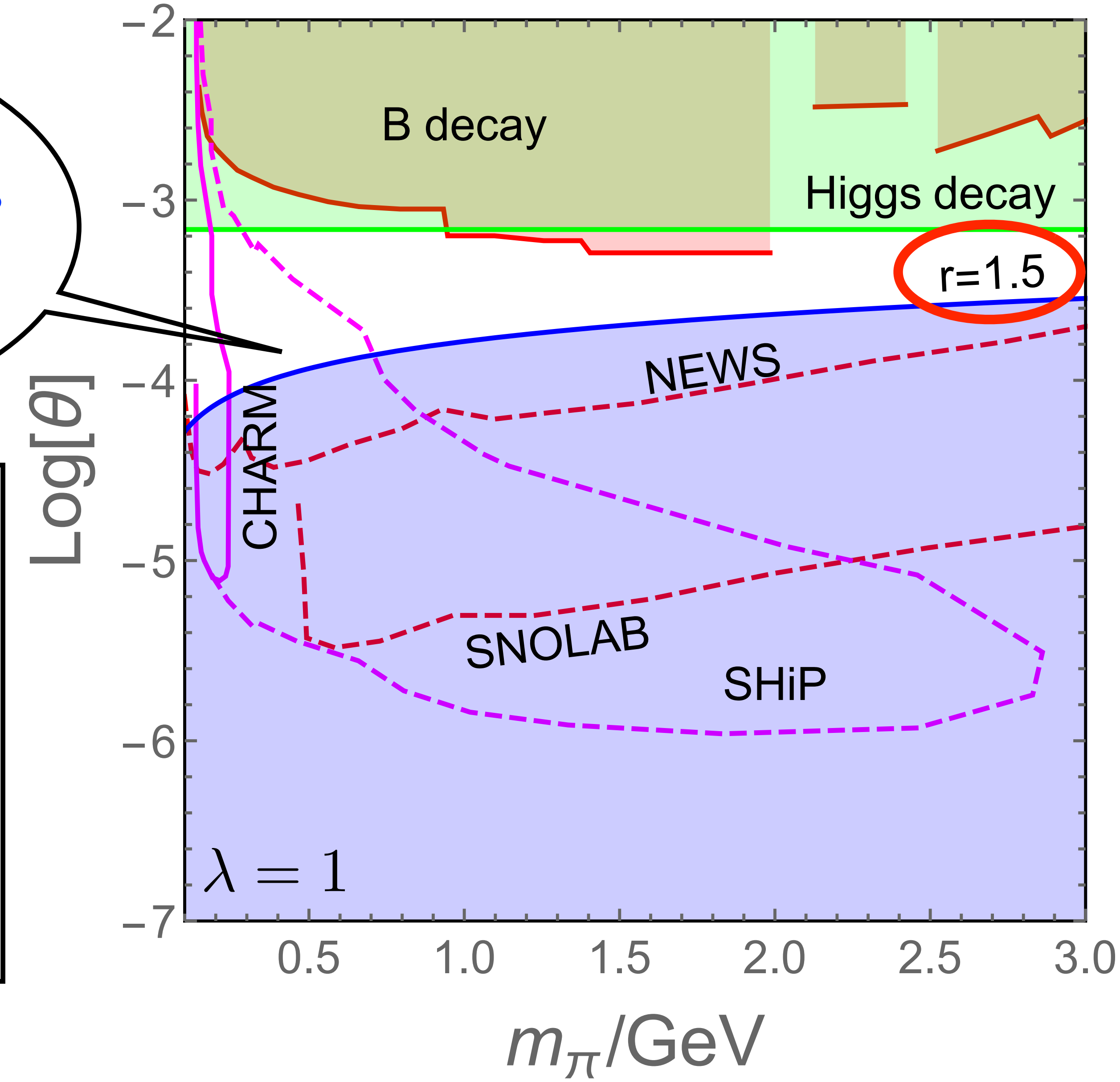
$$\mathcal{L}_{\rm CP} = \frac{m_\pi^2}{4N_f^2 f^2}\left(\pi^a\right)^2 \phi^2 - \frac{1}{6f_\pi^2} r_{abcd}\left(\partial_\mu \pi^a\right)\left(\partial^\mu \pi^b\right)\pi^c \pi^d + \frac{m_\pi^2}{6N_f f_\pi f} d_{abc}\pi^a \pi^b \pi^c \phi + \frac{m_\pi^2}{12 f_\pi^2} c_{abcd}\pi^a \pi^b \pi^c \pi^d$$

$$\mathcal{L}_{\rm CPV} = \tan\left(\theta_H / N_f\right)\left[\frac{m_\pi^2}{2N_f f}\phi(\pi^a)^2 + \frac{m_\pi^2}{6f_\pi} d_{abc}\pi^a \pi^b \pi^c - \frac{m_\pi^2}{30 f_\pi^3}\pi^a \pi^b \pi^c \pi^d \pi^e c_{abcde}\right]$$

# Viable parameter region in a Higgs-portal model

To suppress $\pi\pi \to ss$ annihilation, we take the hidden Higgs mass heavier than the pion mass: $r = m_s/m_\pi \gtrsim 1$

Above this line, kinetic equilibration is sufficient



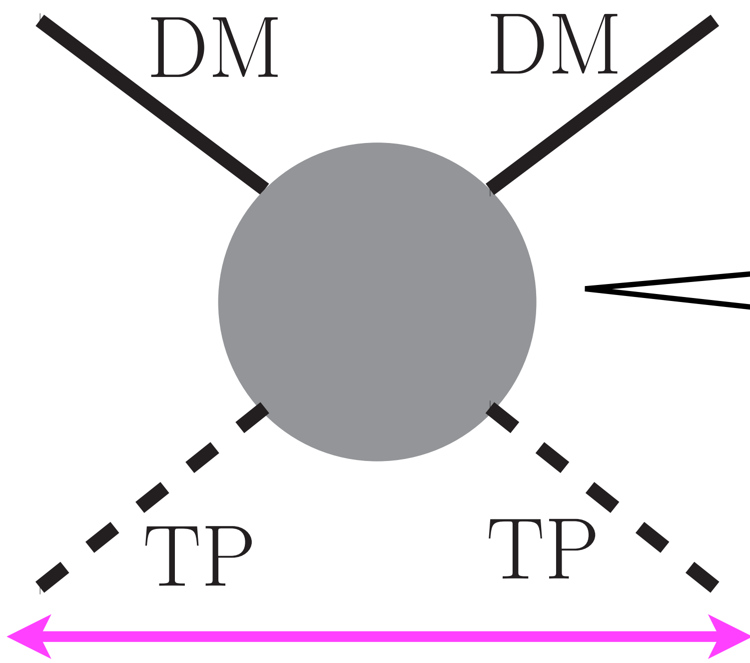

The quark mass term respects a vector-like symmetry that is unbroken even after the chiral condensation (↔ subscript of $i$):

$$\mathcal{L}_{\rm mass} = \lambda s q_i \bar{q}_i$$

AK, Yamada, Yanagida, and Yonekura, PRD, 2016

Viable parameter region will be covered by higher-energy beam dump experiments such as the SHiP experiment and the low-threshold DM direct detection experiments such as NEWS and SNOLAB

# ALP portal




The interaction strength is suppressed by the ALP decay constant ( $f$ ).

Off-shell exchange of the ALP ( $\phi$ ):
the elastic scattering is not sufficiently rapid to keep the DM pions in kinetic equilibrium with the SM plasma

➡ The decay and inverse decay of the ALP keeps it in thermal equilibrium
Thermalized (on-shell) ALP: $\pi\phi \to \pi\phi$ elastic scattering
→ Not sufficiently rapid, too
ONLY $\pi\pi \to \pi\phi$ semi-annihilation is available

# Constraints on semi-annihilation to an ALP

Indirect searches of DM semi-annihilation constrain its cross section severely

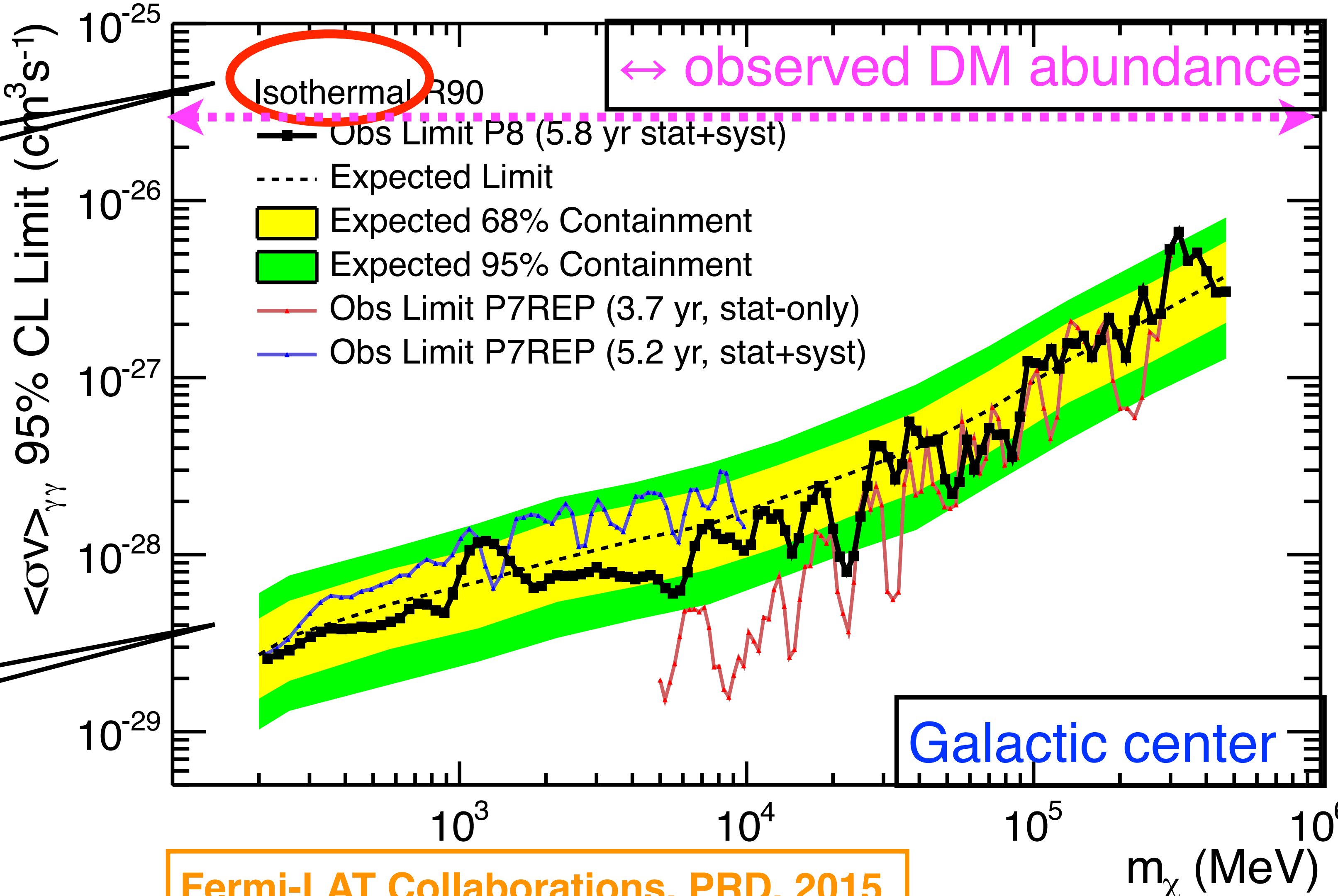
When both the masses are degenerate, $m_\pi = m_\phi$ , the semi-annihilation cross section is proportional to the relative velocity:

$\langle \sigma_{\rm semi} v_{\rm rel} \rangle = \langle \sigma_{\rm semi} v_{\rm rel} \rangle_{\rm fo} \left( v_{\rm rel} / v_{\rm rel,\, fo} \right)$ where

$v_{\rm rel,\, fo} \simeq 0.5 \simeq 2 \times 10^5 \, {\rm km/s}$

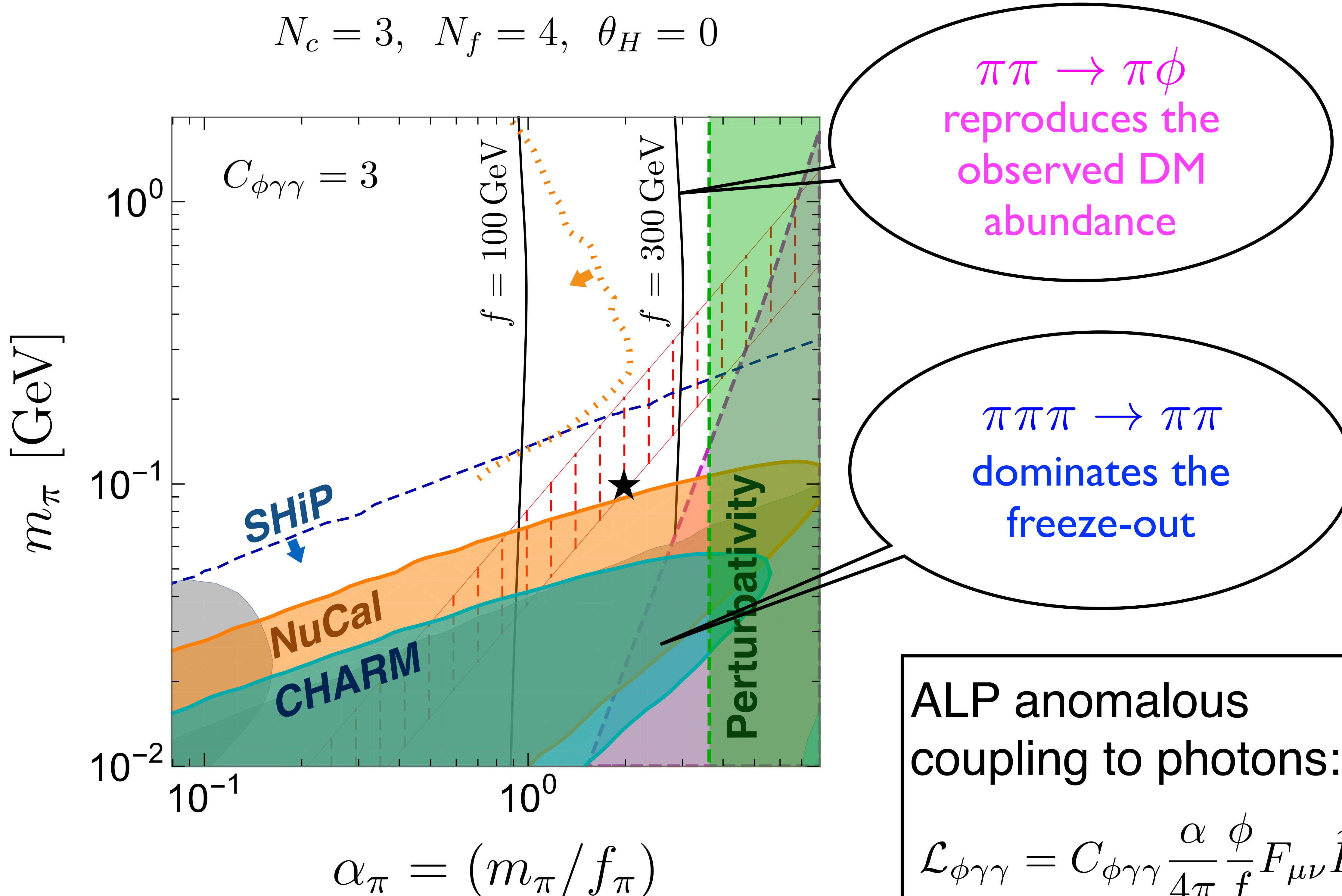
SIDM follows the isothermal profile

$v_{\rm rel,\, obs} \lesssim 200 \, {\rm km/s}$ satisfies the upper bound




Fermi-LAT Collaborations, PRD, 2015

# Viable parameter region in an ALP-portal model




ALP anomalous coupling to photons:

$$\mathcal{L}_{\phi\gamma\gamma} = C_{\phi\gamma\gamma}\frac{\alpha}{4\pi}\frac{\phi}{f}F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

AK, Hyungjin Kim, and Sekiguchi, PRD, 2017

Viable parameter region will be covered by higher-energy beam dump experiments such as the ShiP experiment

# Asymptotic temperature

non-relativistic limit:

$$x\frac{d}{dx}\left(\frac{x_\chi}{x}\right) \approx \frac{x_\chi}{x} - (\gamma - 1)\frac{2x_{\rm fo}}{3}\left(\frac{Y_\chi}{Y_{\chi,\infty}}\right)\left(\frac{x_\chi}{x}\right)^2$$

adiabatic cooling

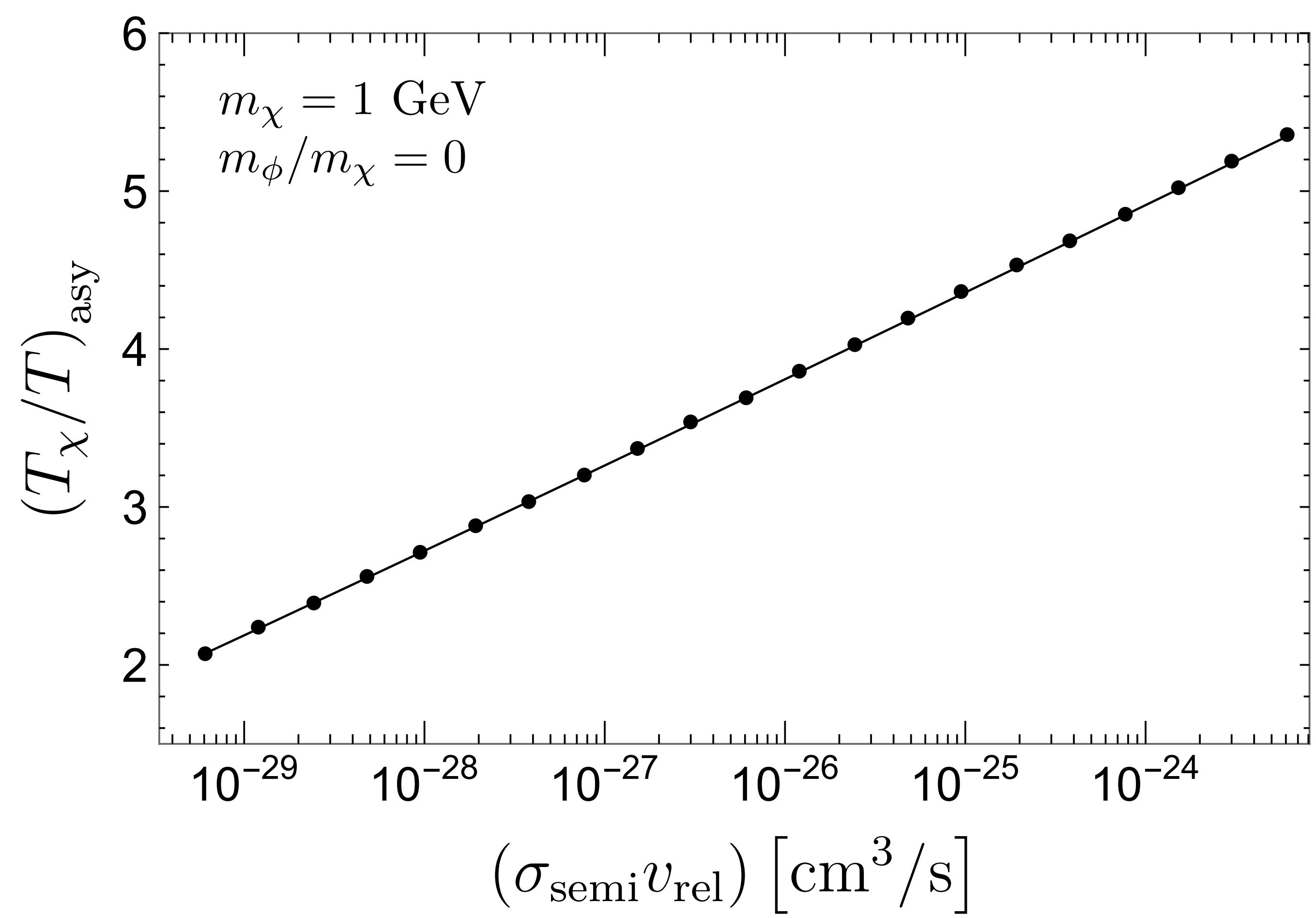
heating through the semi-annihilation

$Y_{\chi,\infty} = x_{\rm fo}/\lambda(x_{\rm fo})$ : relic yield

$\gamma = \frac{5}{4}\left(1 - \frac{m_\phi^2}{5m_\chi^2}\right)$ : Lorentz boost of the DM in the final state

balance between adiabatic cooling and heating through the semi-annihilation:

$$\left(\frac{T_\chi}{T}\right)_{\rm asy} \simeq (\gamma - 1)\frac{2x_{\rm fo}}{3} \propto \ln(\sigma_{\rm semi} v_{\rm rel})$$

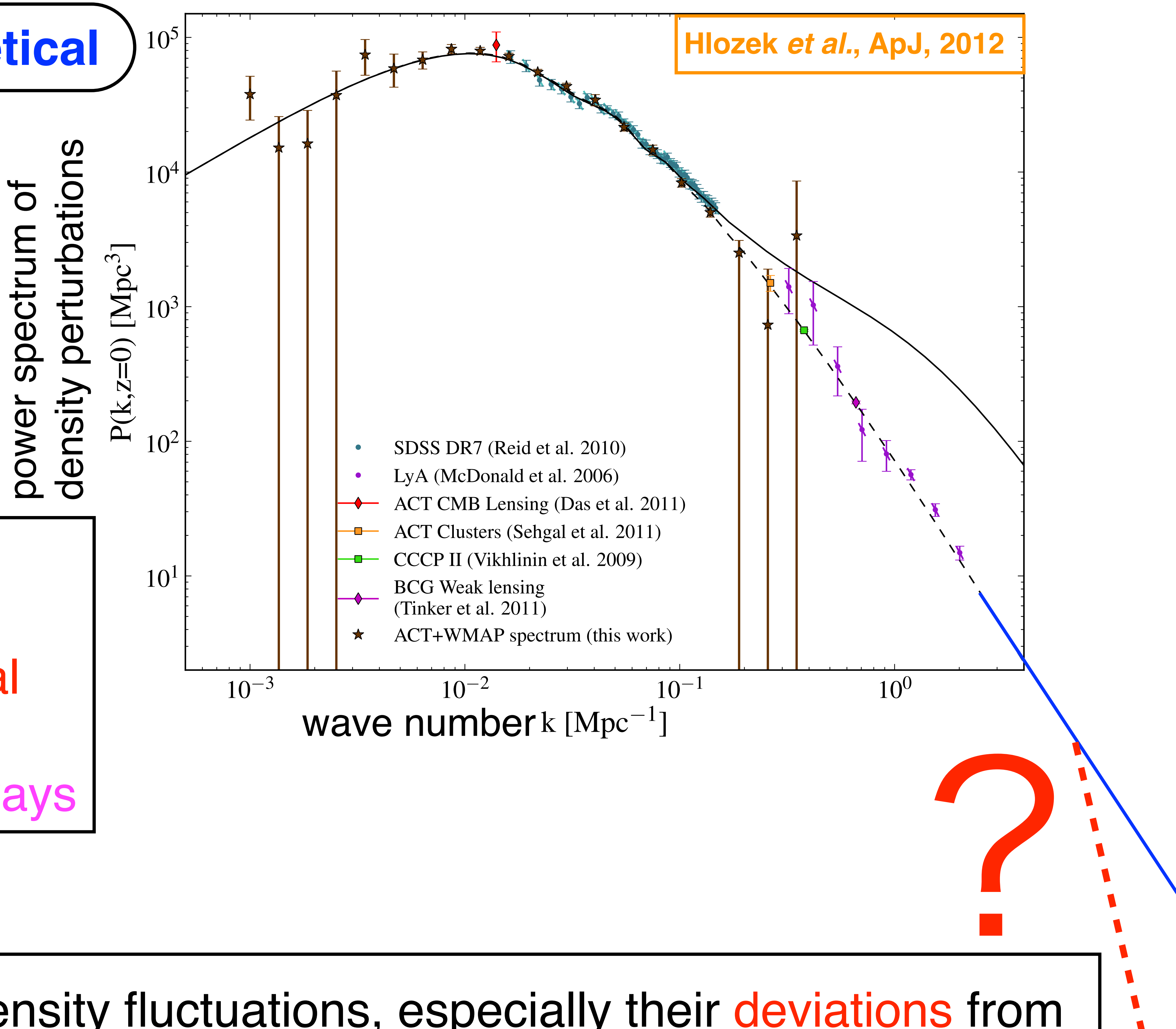


# Cold Dark Matter?

hypothetical

cold dark matter:
null thermal velocity
only gravitationally interacting

particle physics DM candidates:
finite (sizable) thermal velocity
interacting in many ways



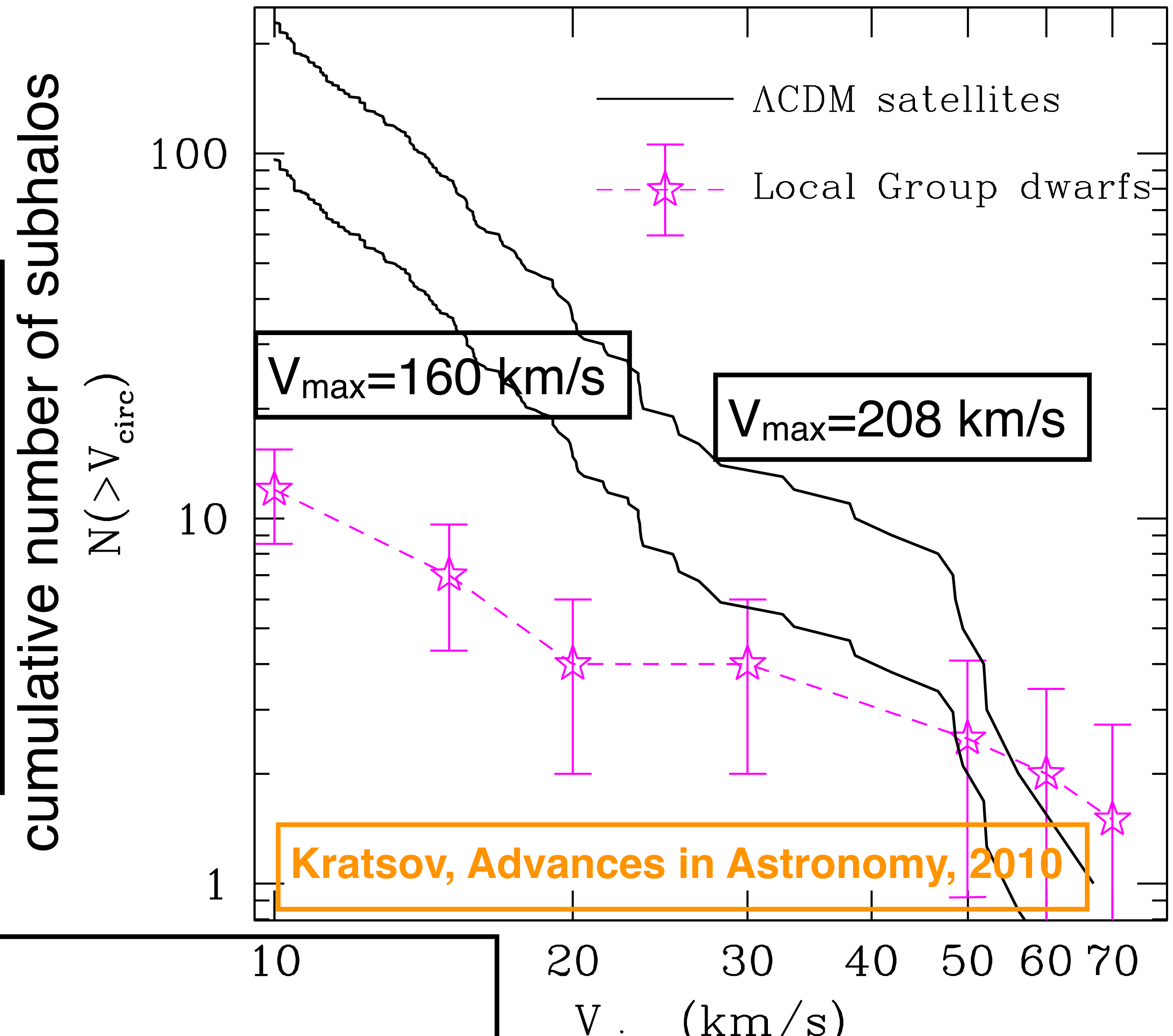

Small scale matter density fluctuations, especially their deviations from the ΛCDM model, contain imprints of the nature of DM

# 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




(maximum) circular velocity

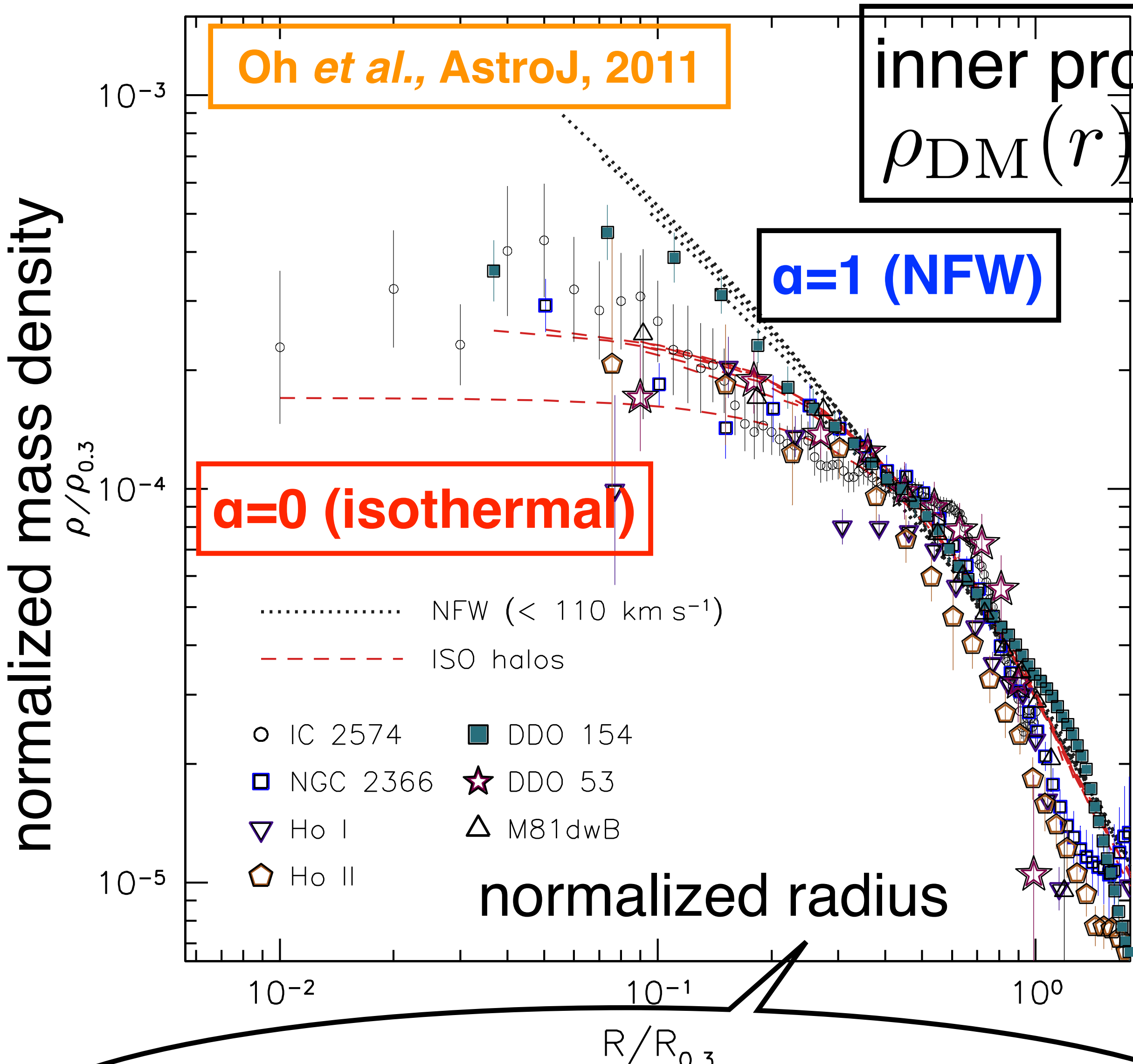
$$V_{\rm circ}^2(r) = \frac{GM(<r)}{r} \qquad V_{\rm max} = \max_r\{V_{\rm circ}(r)\}$$

maximal circular velocity of subhalo

# Small scale crisis II

**cusp vs core problem**

*N*-body (DM-only) simulations in the ΛCDM model →
**UNIVERSAL** 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:
$$\rho_{\rm DM}(r) = \frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

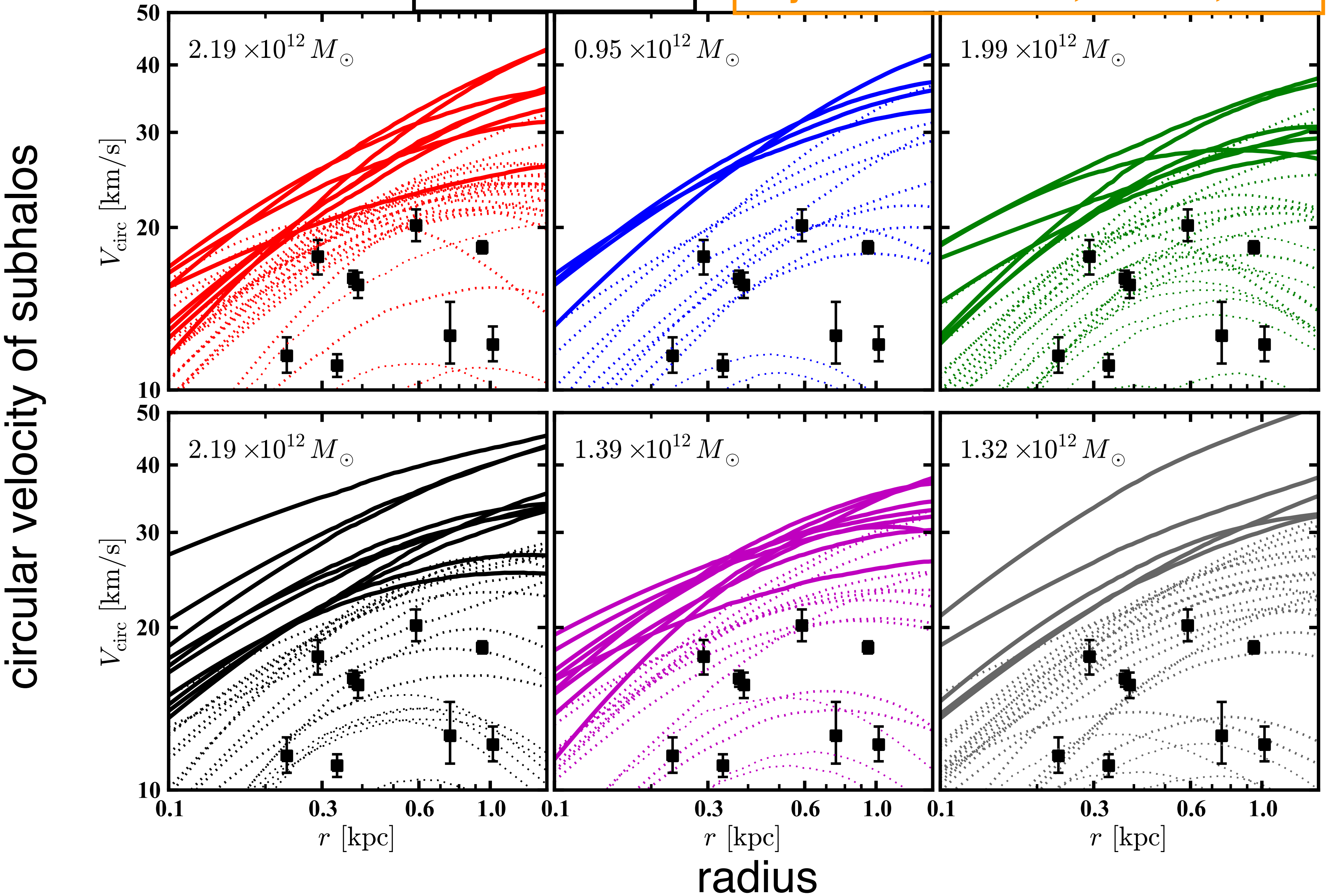
isothermal profile:
$$\rho_{\rm DM}(r) = \rho^0_{\rm DM}\begin{cases} 1 & (r \ll r_0) \\ (r_0/r)^2 & (r \gg r_0) \end{cases}$$

# Small scale crisis III

**too big to fail problem**

MW-like halos

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



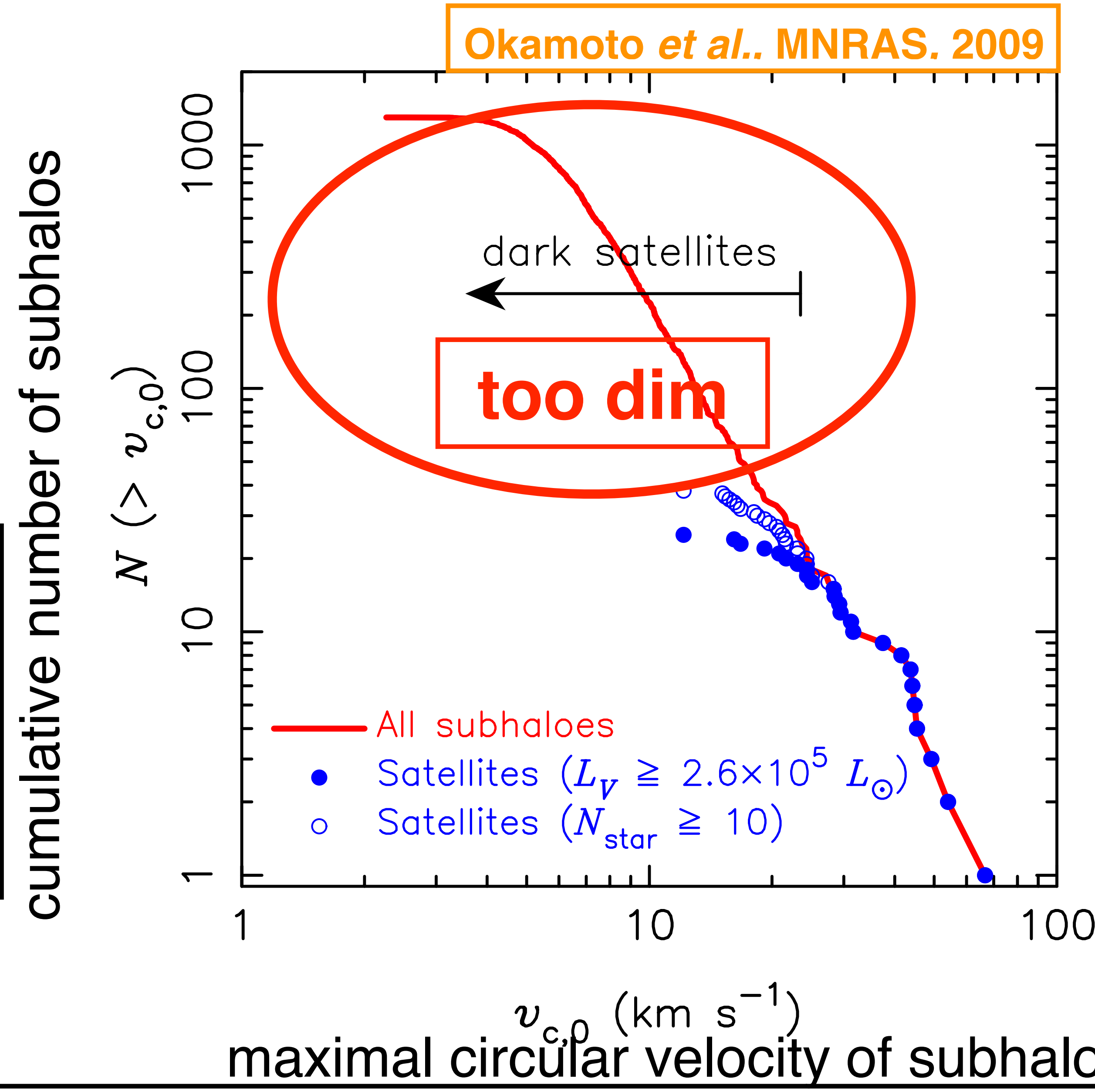

*N*-body (DM-only) simulations in ΛCDM model →
~10 subhalos with deepest potential wells in Milky Way-size halos
**DO NOT HOST** observed counterparts (dwarf spheroidal galaxies)

# Possible solution I

Above Discussions are based on *N*-body (**DM-only**) simulations in the ΛCDM model

↕

Gravitational potentials are shallower at smaller scales →
**BARYONIC HEATING** and **COOLING** processes may be important




## Baryonic processes

- **heating from ionizing photons** - ionizing photons emitted and spread around reionization of the Universe heat and evaporate gases

- **mass loss by supernova explosions** - supernova explosions blow gases from inner region → DM redistribute along shallower potential

# Possible solution II

Above Discussions are based on
*N*-body (DM-only) simulations in the ΛCDM model

↕

**alternative models ↔ nature of DM**

- **warmness** - thermal velocities induce pressure of DM fluid and prevent gravitational growth (Jeans analysis)

- **interactions with relativistic particles** - DM fluid couples to relativistic particles in a direct/indirect manner

- **self-interaction** - induced heat transfer of DM fluid heats DM particles in inner region and flatten inner profile

# Concentration-mass relation

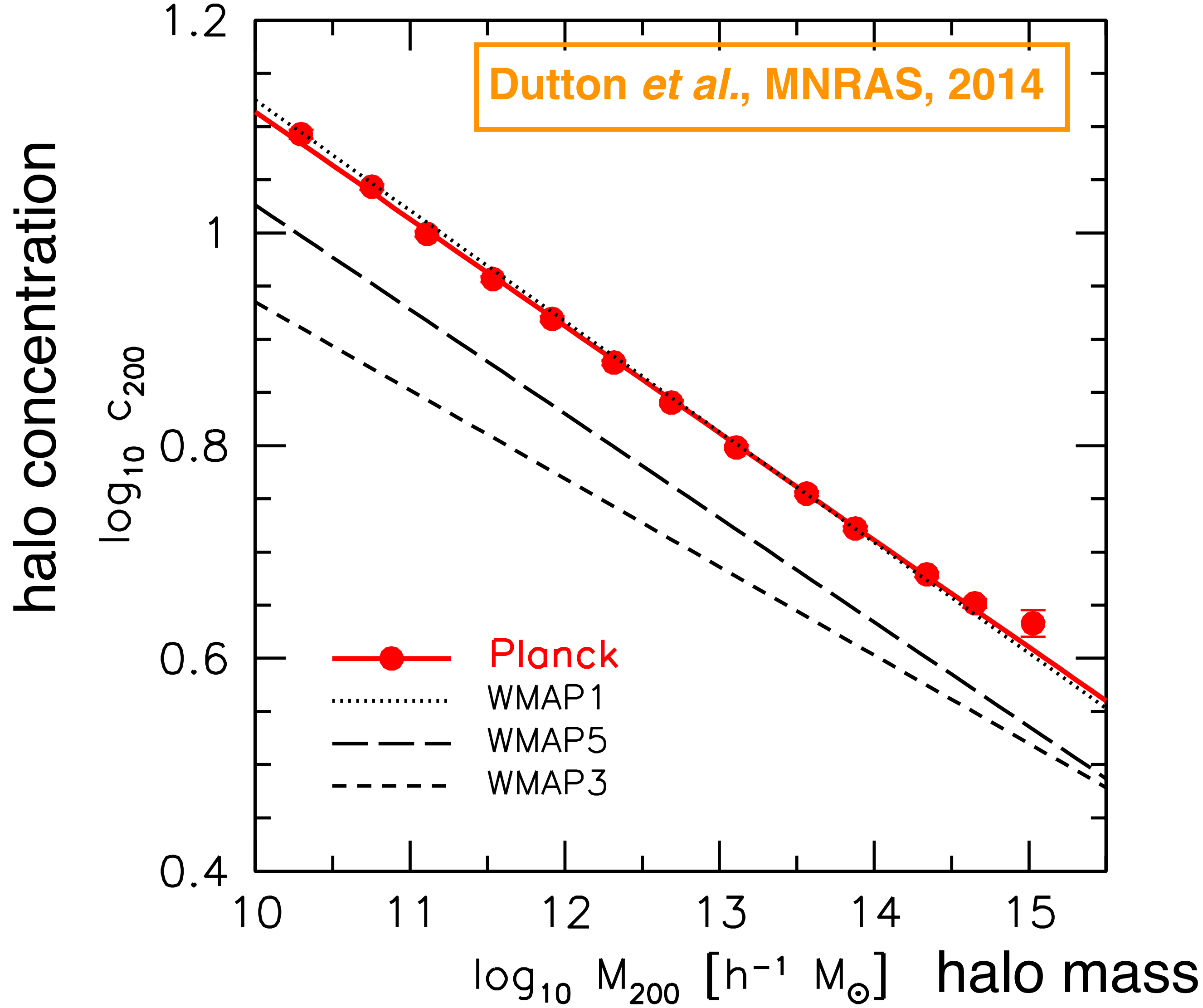
Why is a simulated rotation curve (almost) **DEFINITE** for a given $V_{max}$?
Two parameters for the NFW profile

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

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

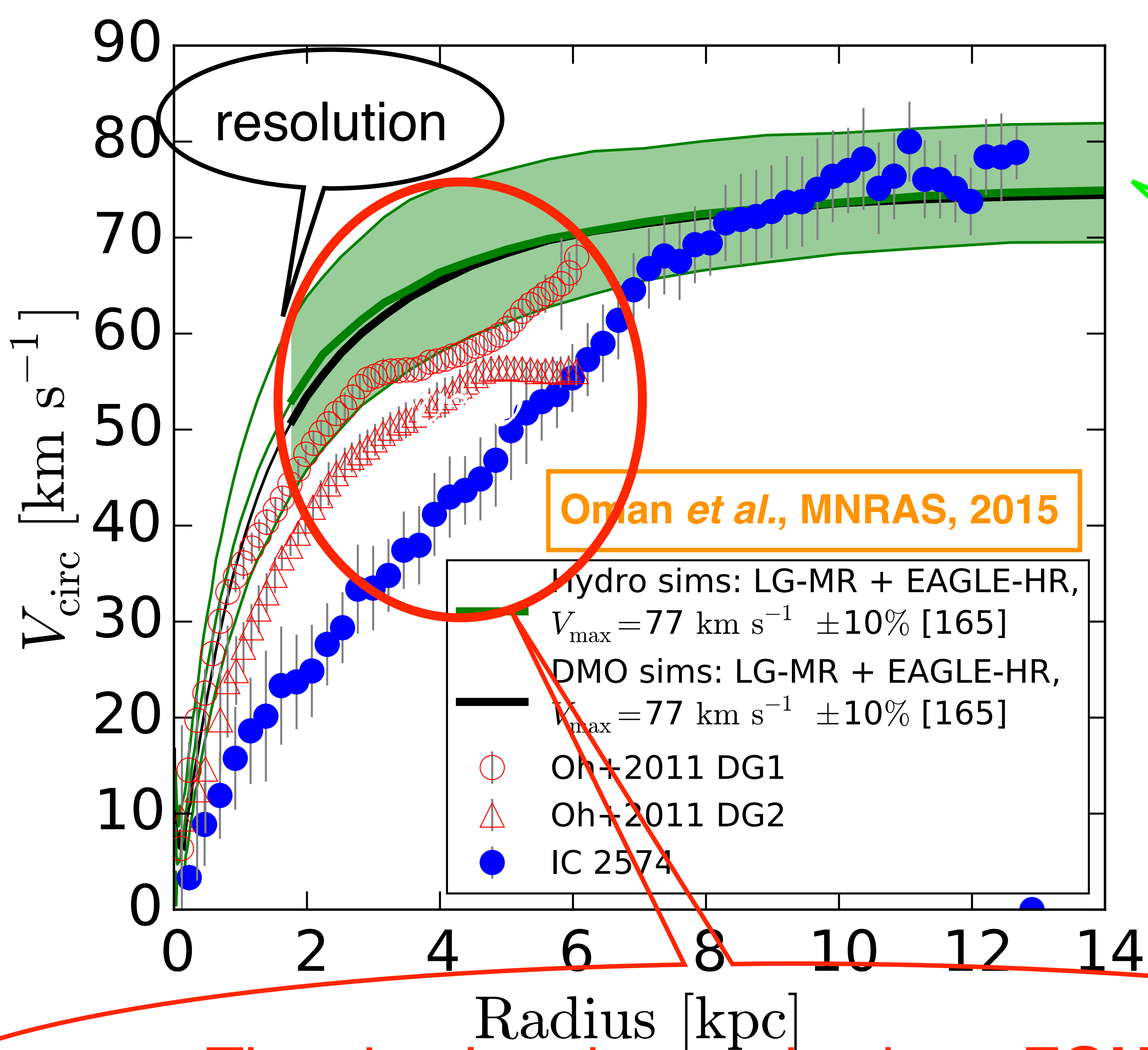



$$c_{200} = r_{200}/r_s$$

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

# Inner mass deficit problem

Rephrasing cusp vs core problem to emphasize that not only the slope but also the **WHOLE MASS DISTRIBUTION** should be examined.

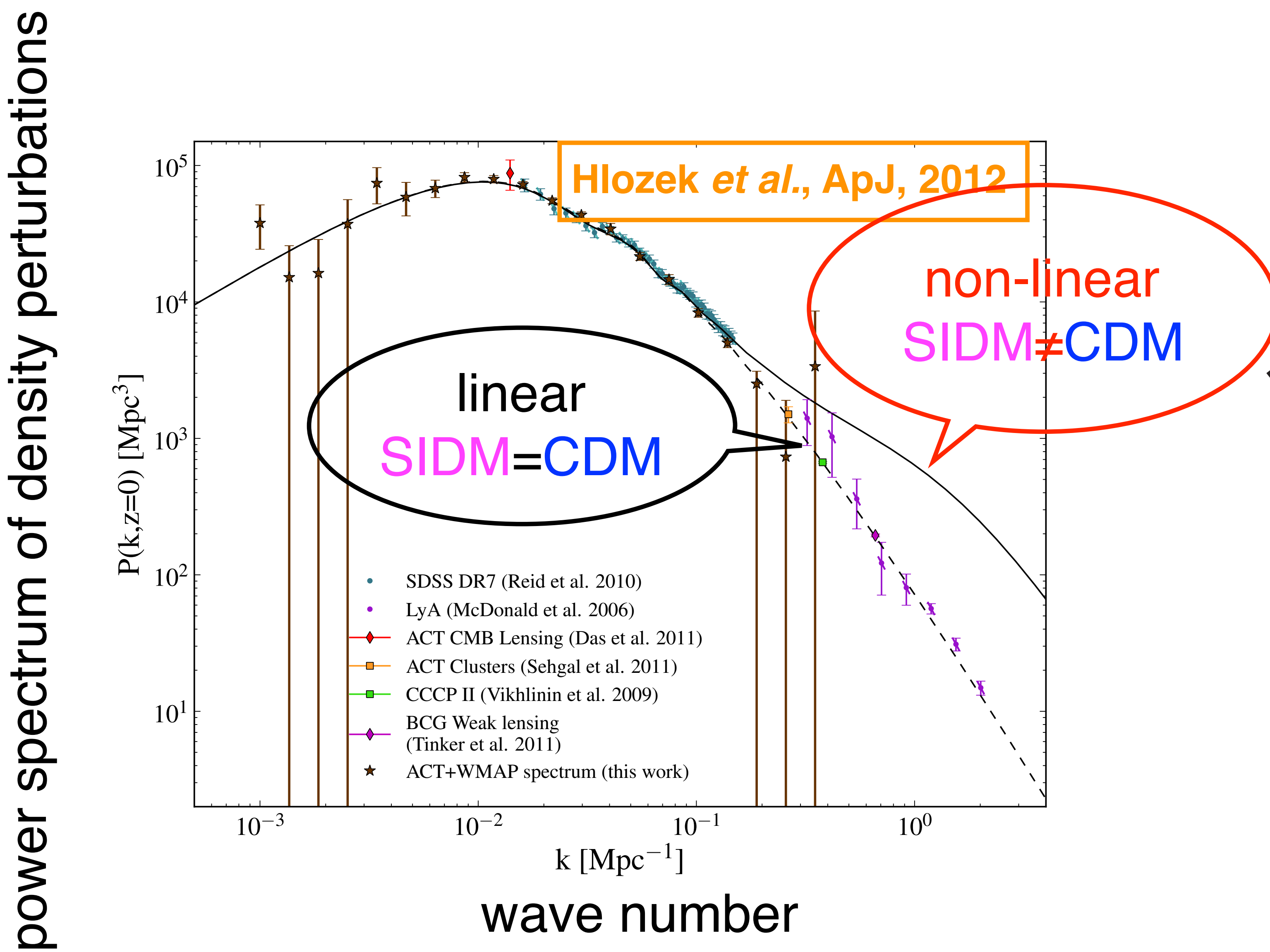


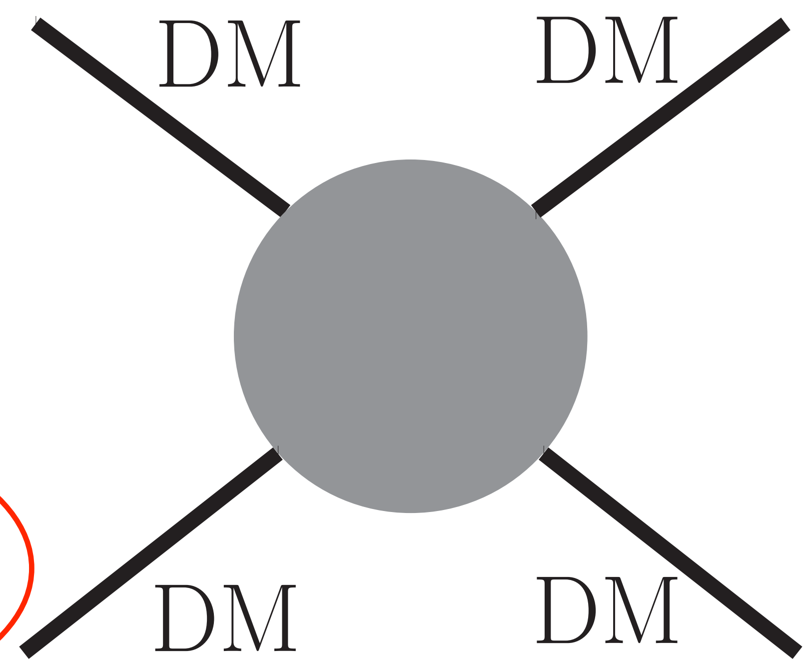

10th-90th percentile range from the state-of-the-art hydrodynamical simulations in the ΛCDM model (*EAGLE, Local GROUPS*) with modeled subgrid baryonic physics (radiative cooling, star formation, stellar and chemical enrichment, energetic stellar feedback, black hole accretion and mergers, and AGN feedback)

The simulated mass is about **FOUR** times higher than the observed!

# 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**

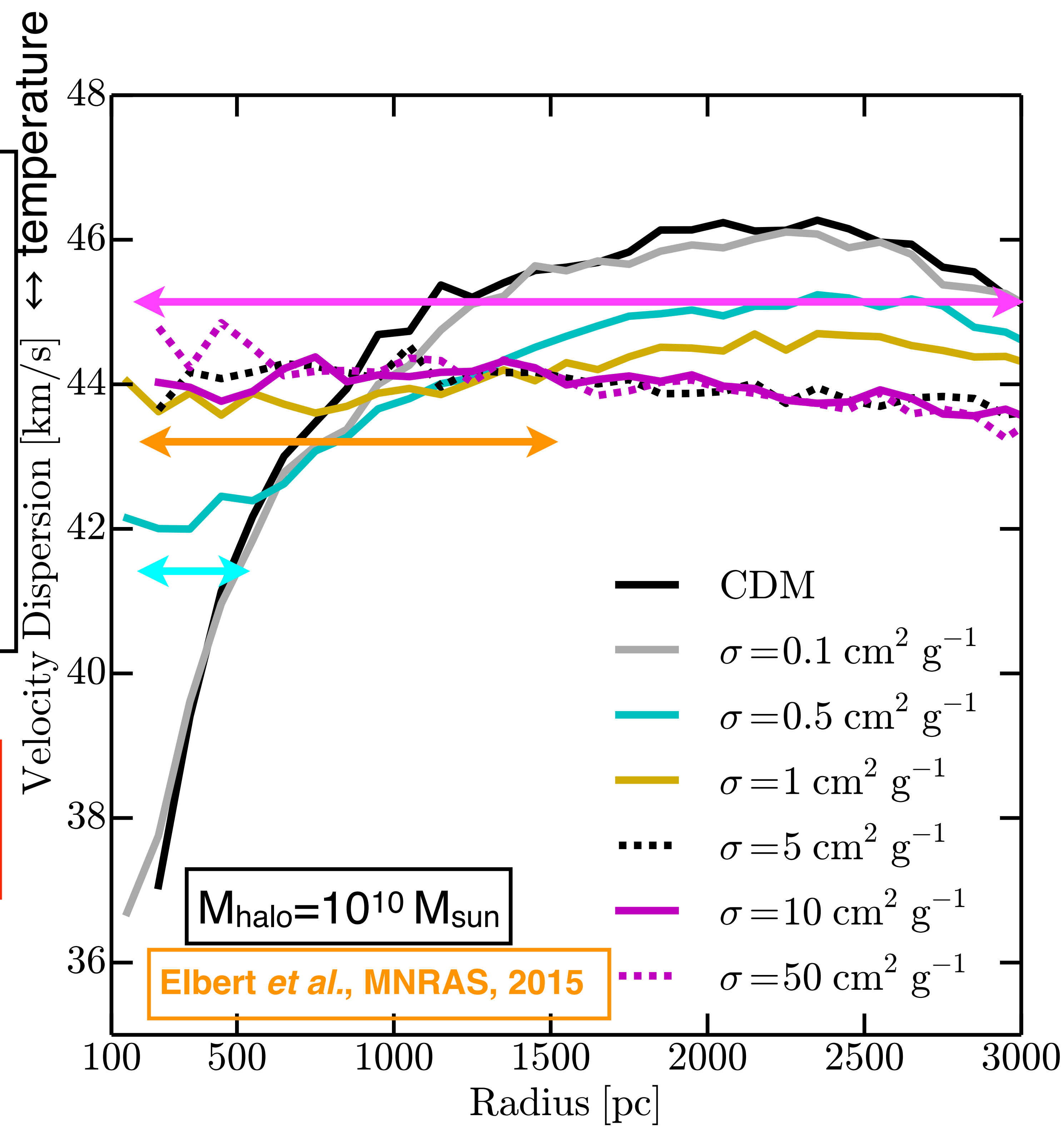
# SIDM halo - velocity dispersion

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

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

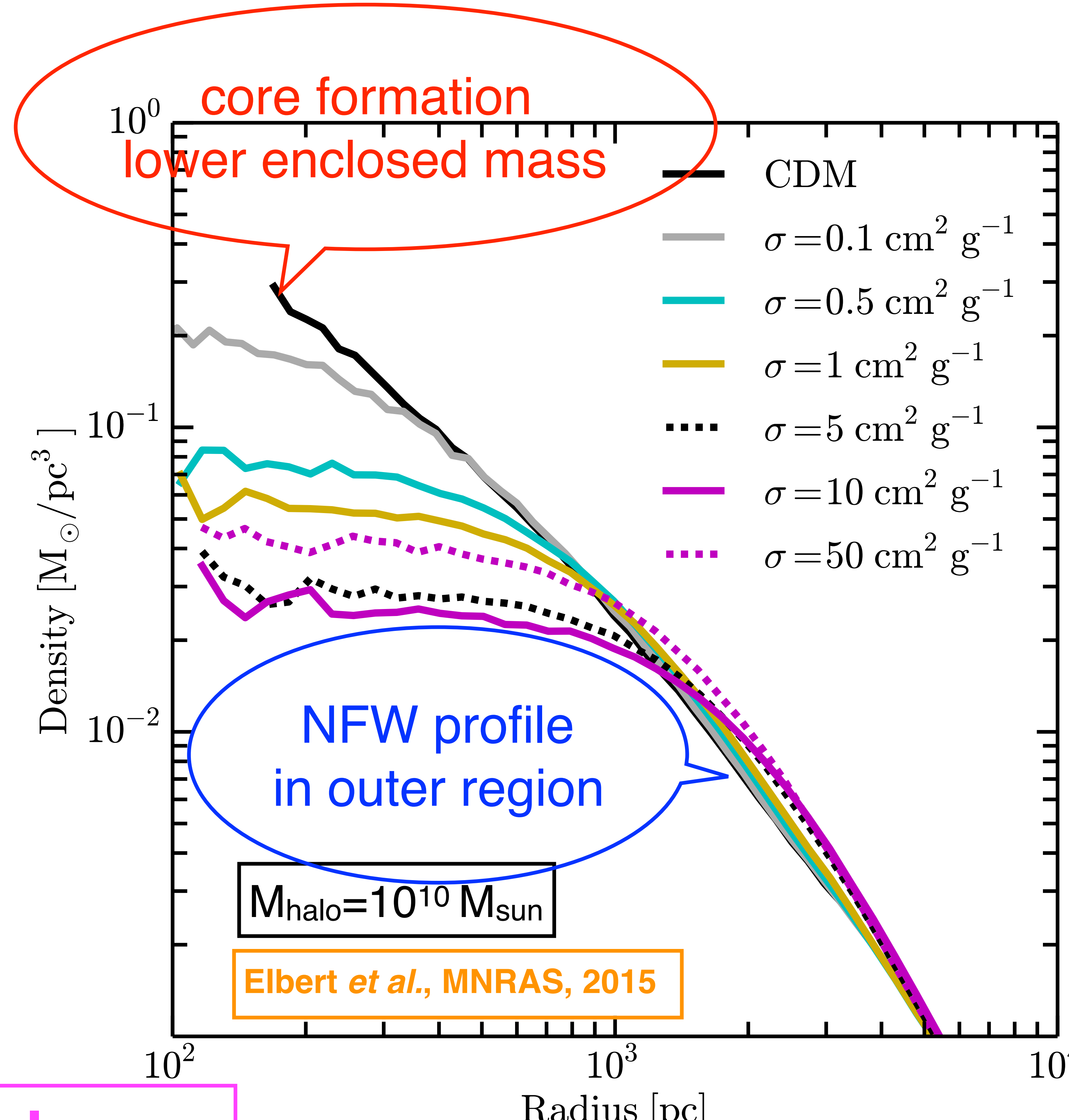


# SIDM halo - mass density

SIDM-only simulation

As σ/m increases,
central density decreases

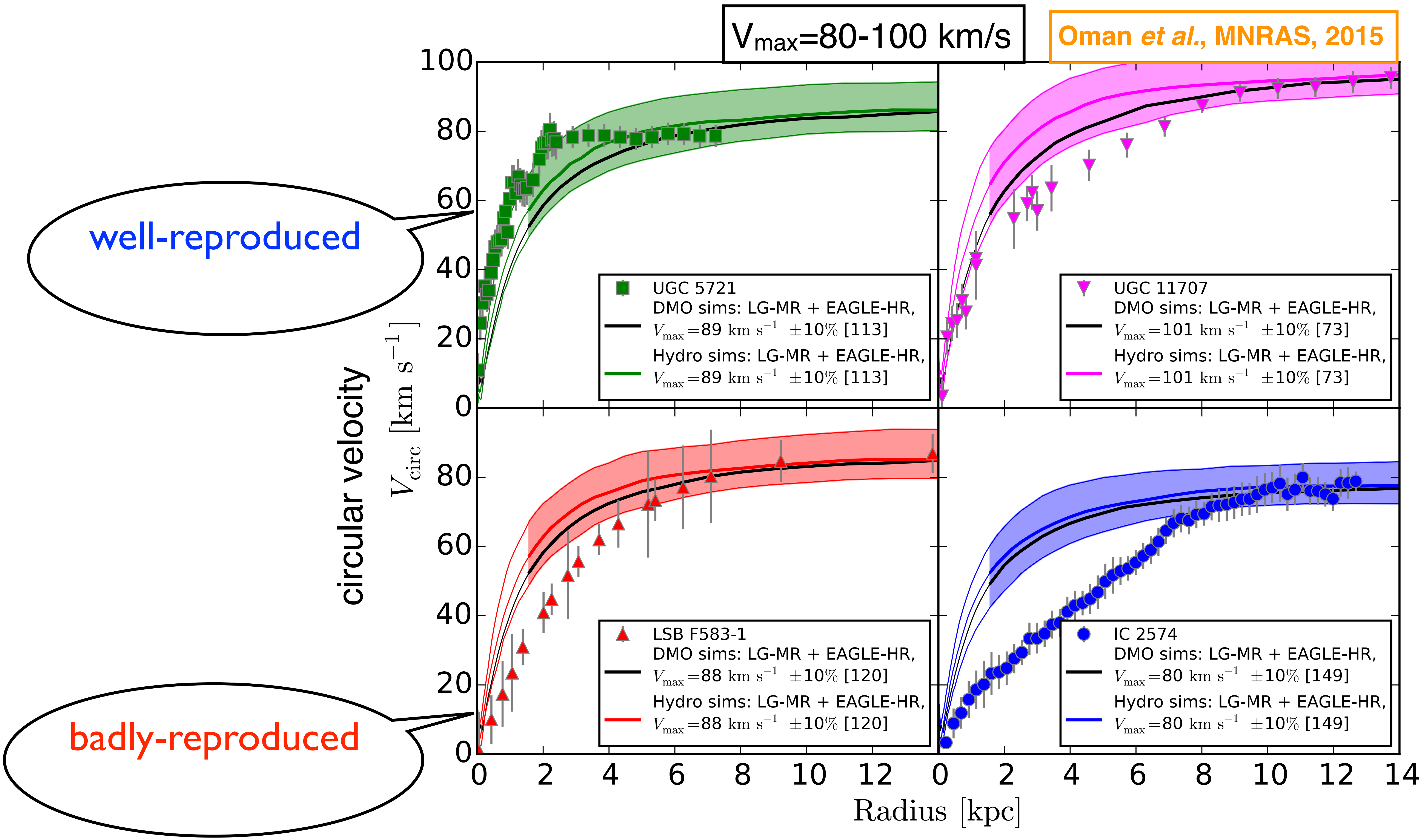
Inverted at some point
← gravo-thermo instability
↔ core-collapse




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

# Unexpected diversity problem

The inner mass deficit is **NOT UNIVERSAL**, but should be elaborated in a **GALAXY-BY-GALAXY** manner even with **$V_{max}$ fixed**.



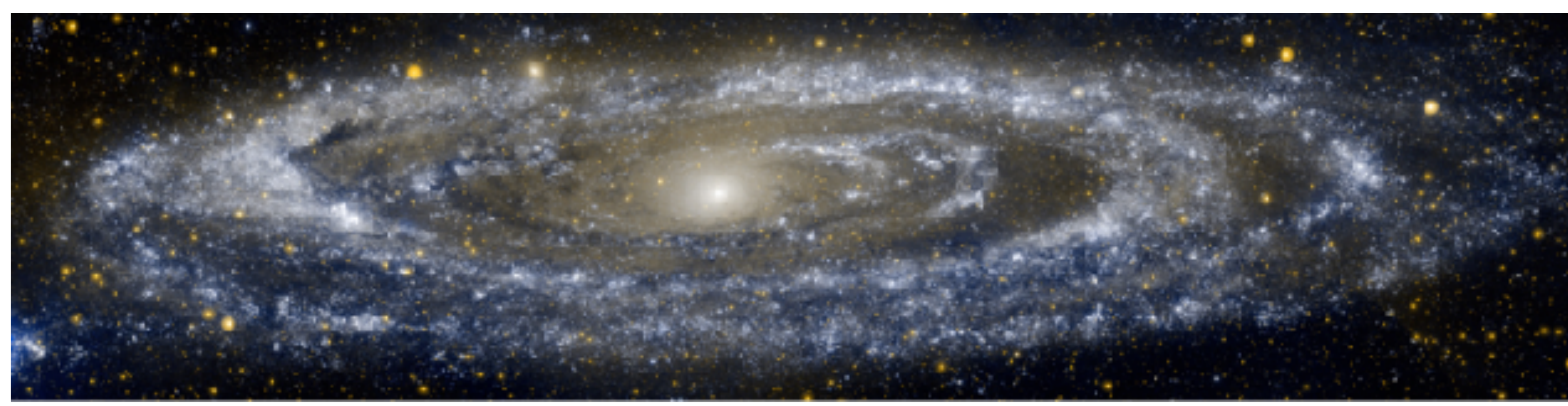
# Origin of the diversity

**Unexpected diversity problem??**

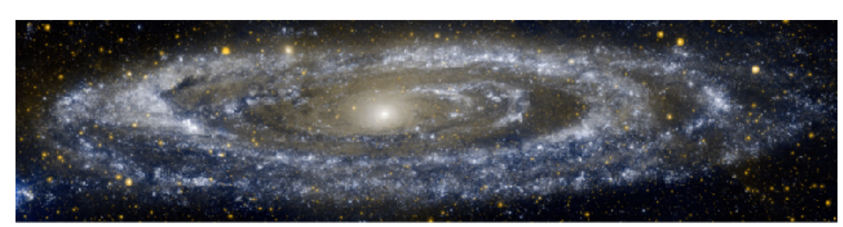
⟺ For a given cross section ($\sigma/m$=3 cm²/g in the following), SIDM halo profile is still **DEFINITE** and characterized by only one parameter $V_{max}$

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

Extended stellar disk



Compact stellar disk



# Influence of the baryons

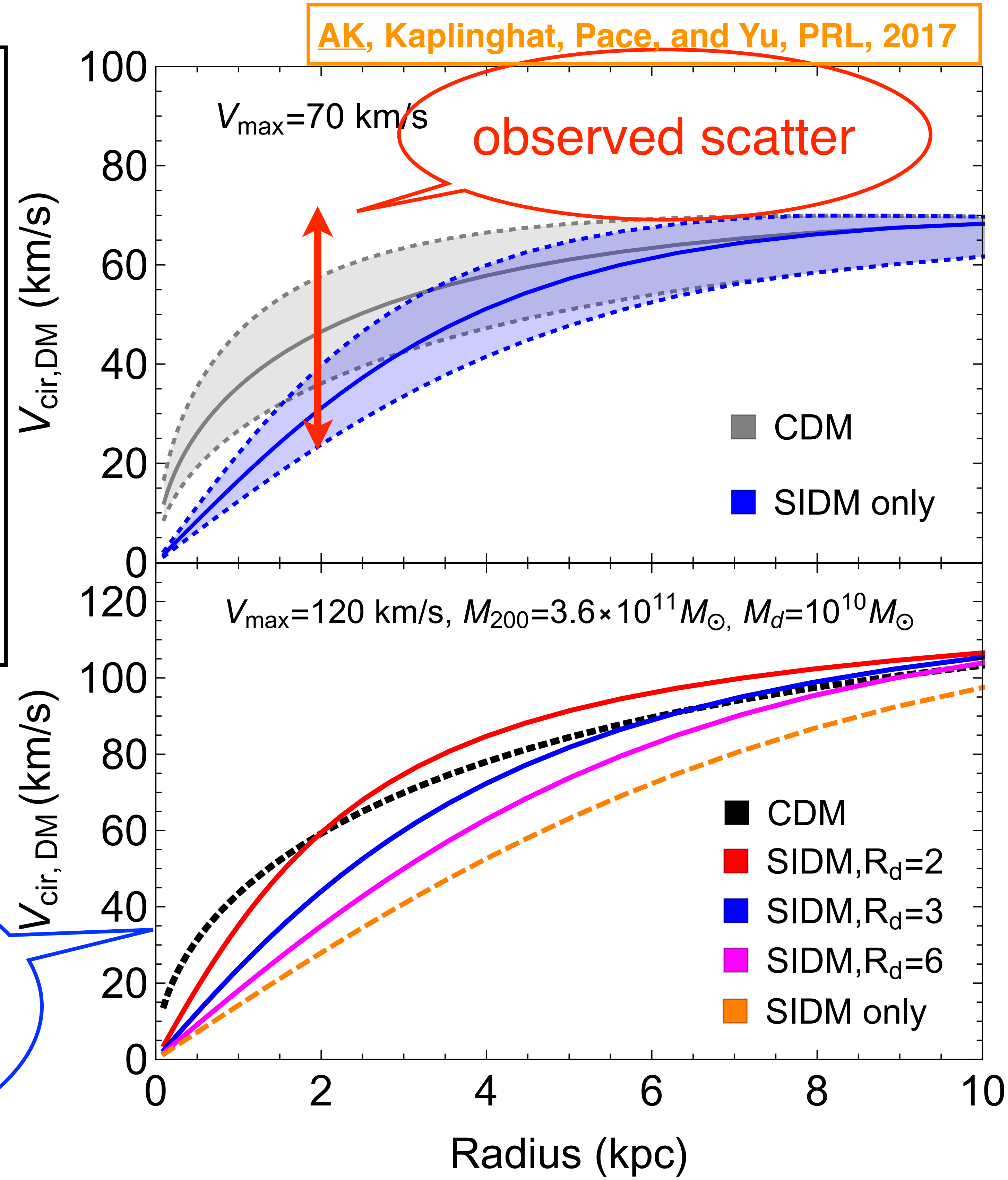
SIDM static distribution with a thin exponential disk potential from the Poisson equation:

$$\Delta\phi = 4\pi G \rho^0_{\rm DM} \exp(-\phi/\sigma^2)$$

$$\phi(0) = 0$$

$$\phi(\vec{x}) \rightarrow V^2_\infty \ln(r/r_0)$$
$$(r = |\vec{x}| \rightarrow \infty)$$

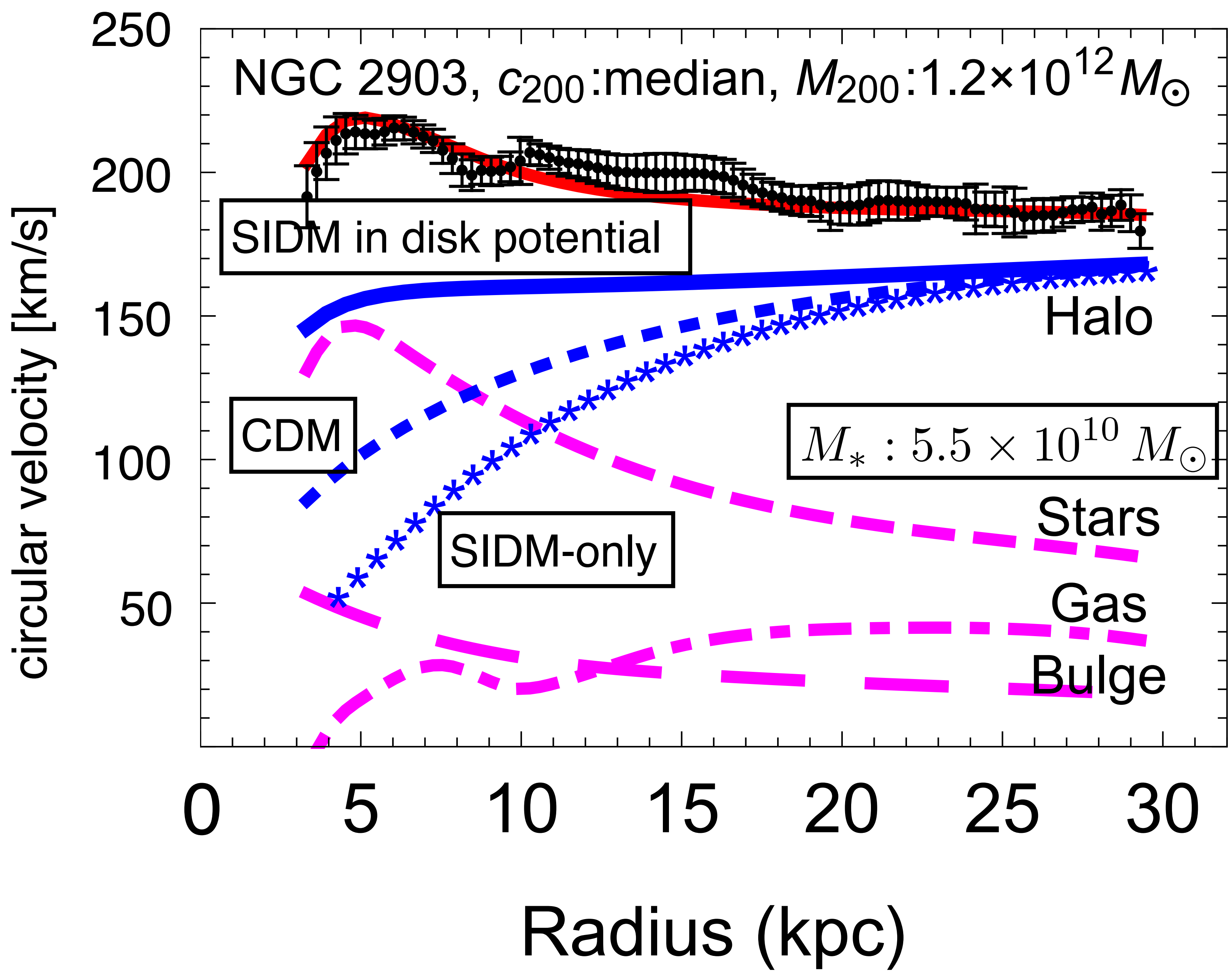
$$V^2_\infty = 2\sigma^2 = 4\pi G \rho^0_{\rm DM} r_0^2$$




SIDM profile **CONTRACTS** under the presence of **COMPACT** stellar disk

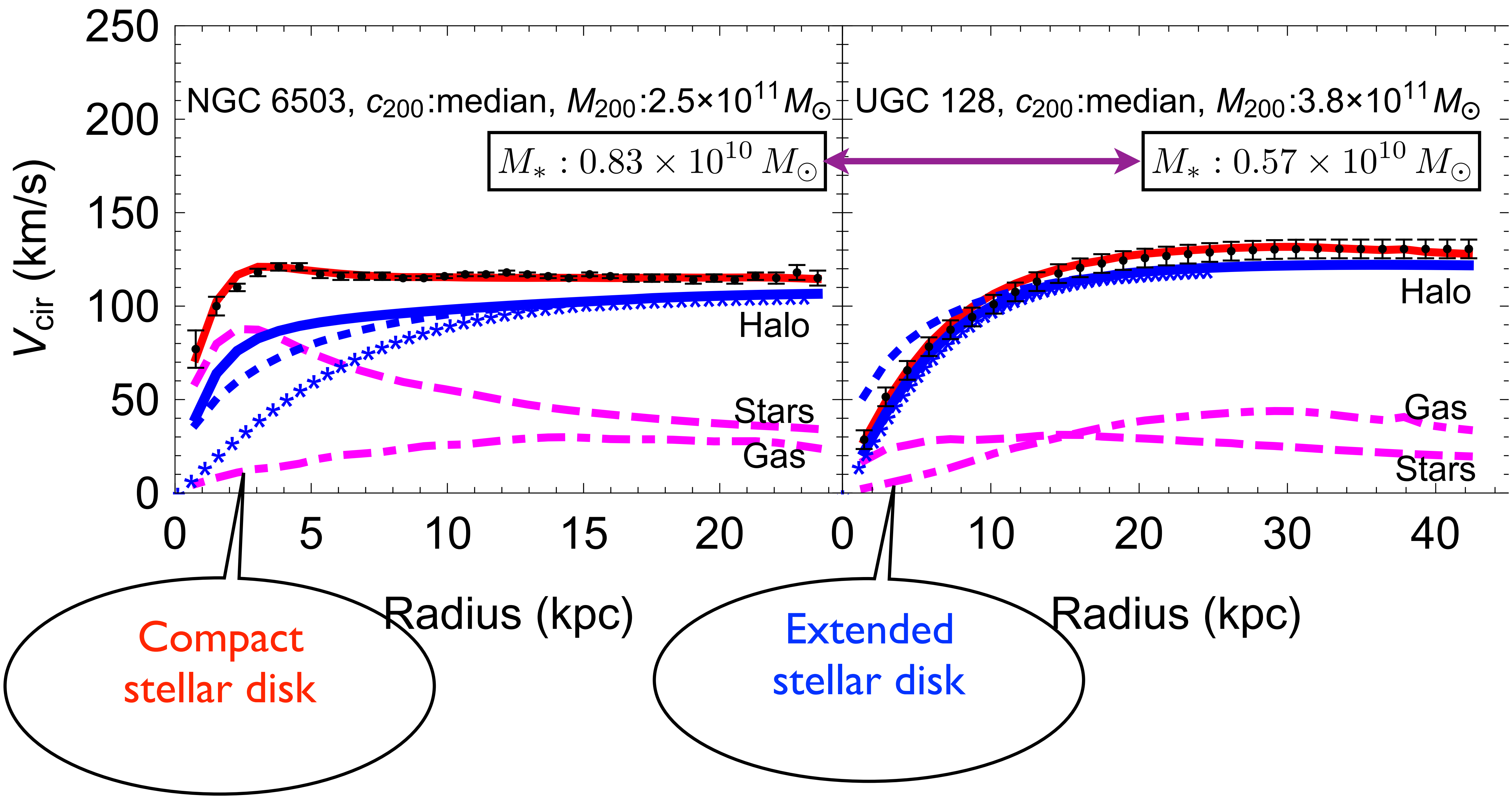
# Case study I

In **MASSIVE** spiral galaxies,
stellar disks can change **WHOLE SIDM MASS DISTRIBUTIONS**



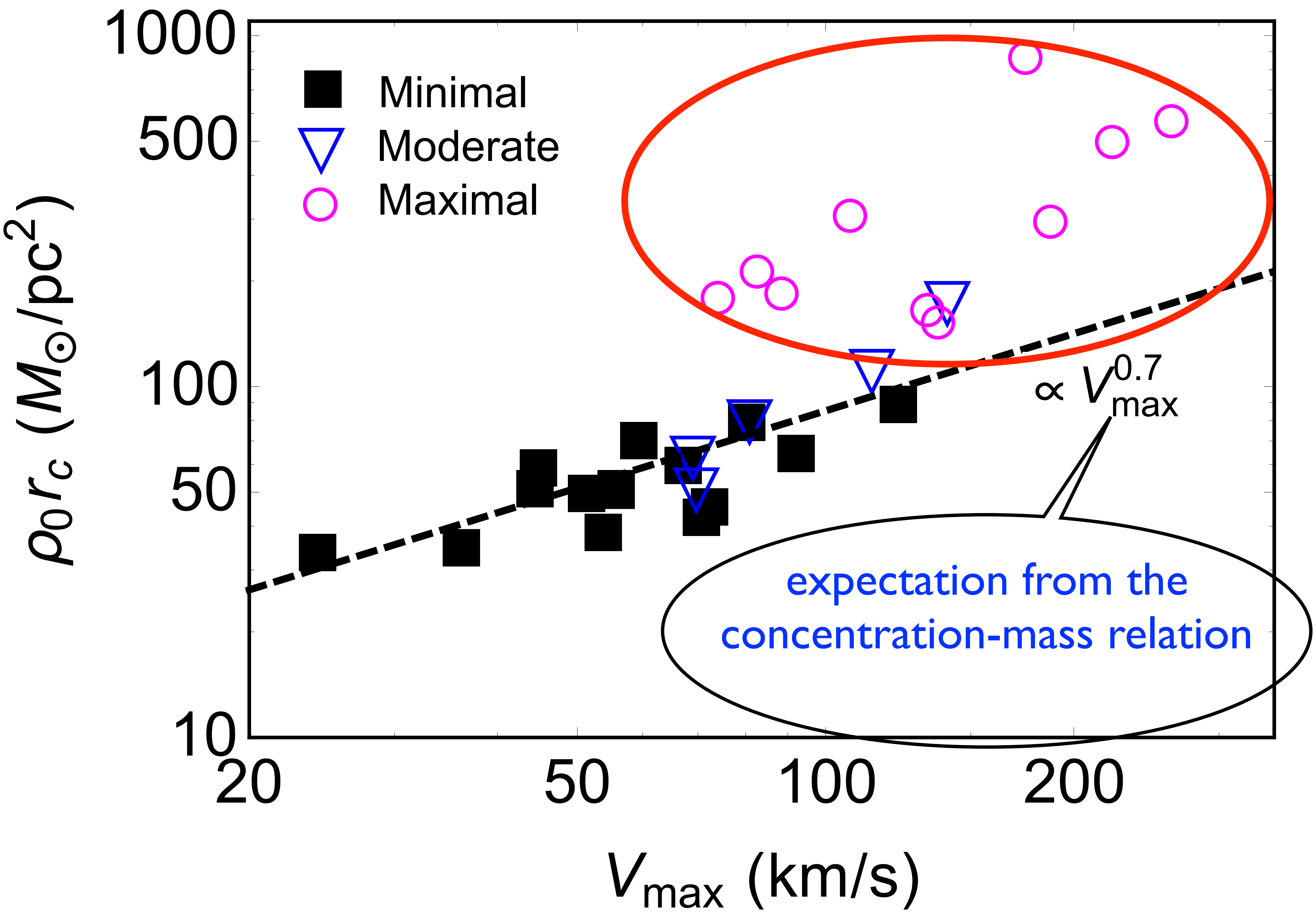
# Case study II

SIDM halo profile reflects **HOW CONTRACTED** the hosted stellar disk is even with similar **$V_{max}$ AND $M_*$**



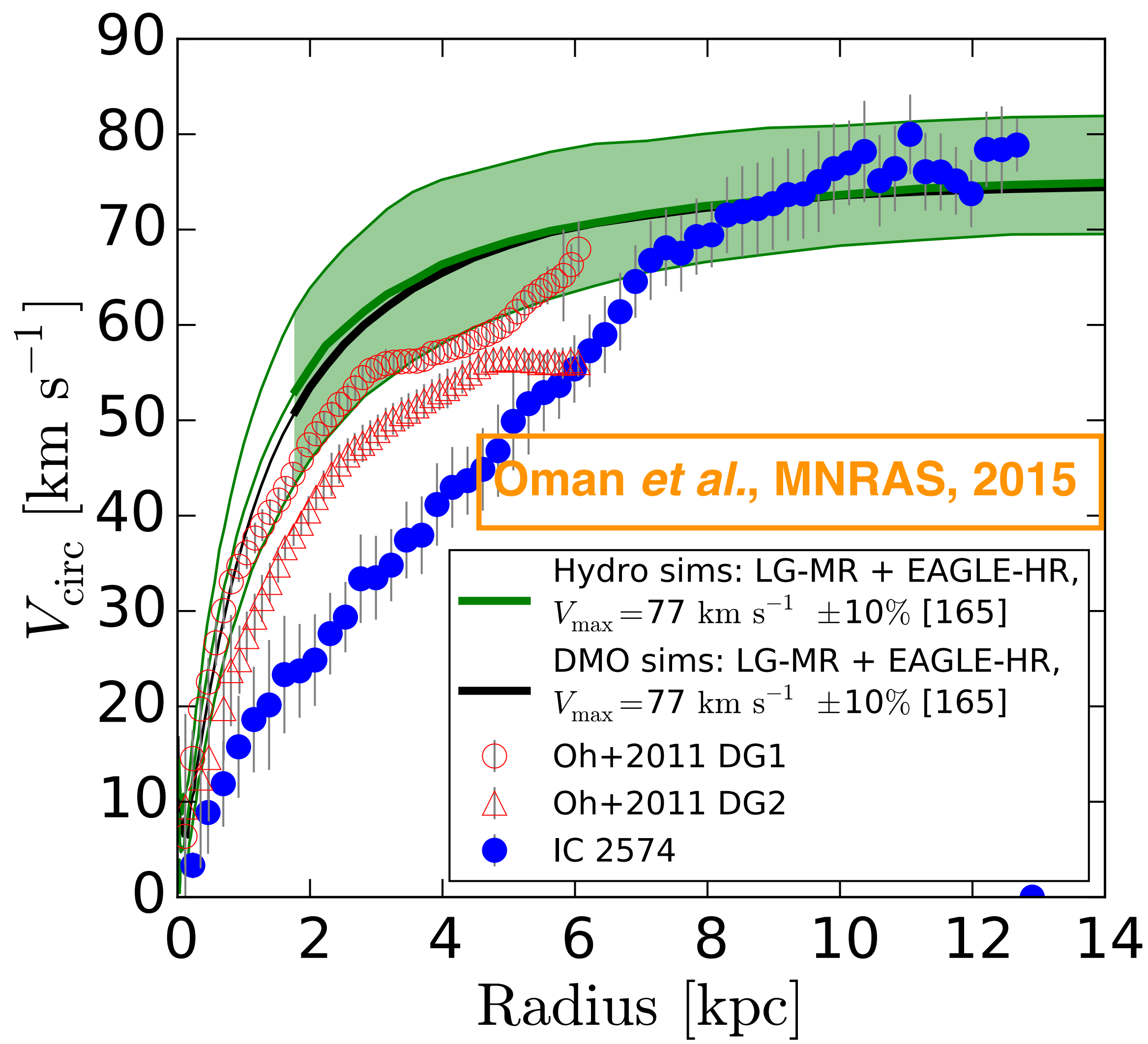
# More samples

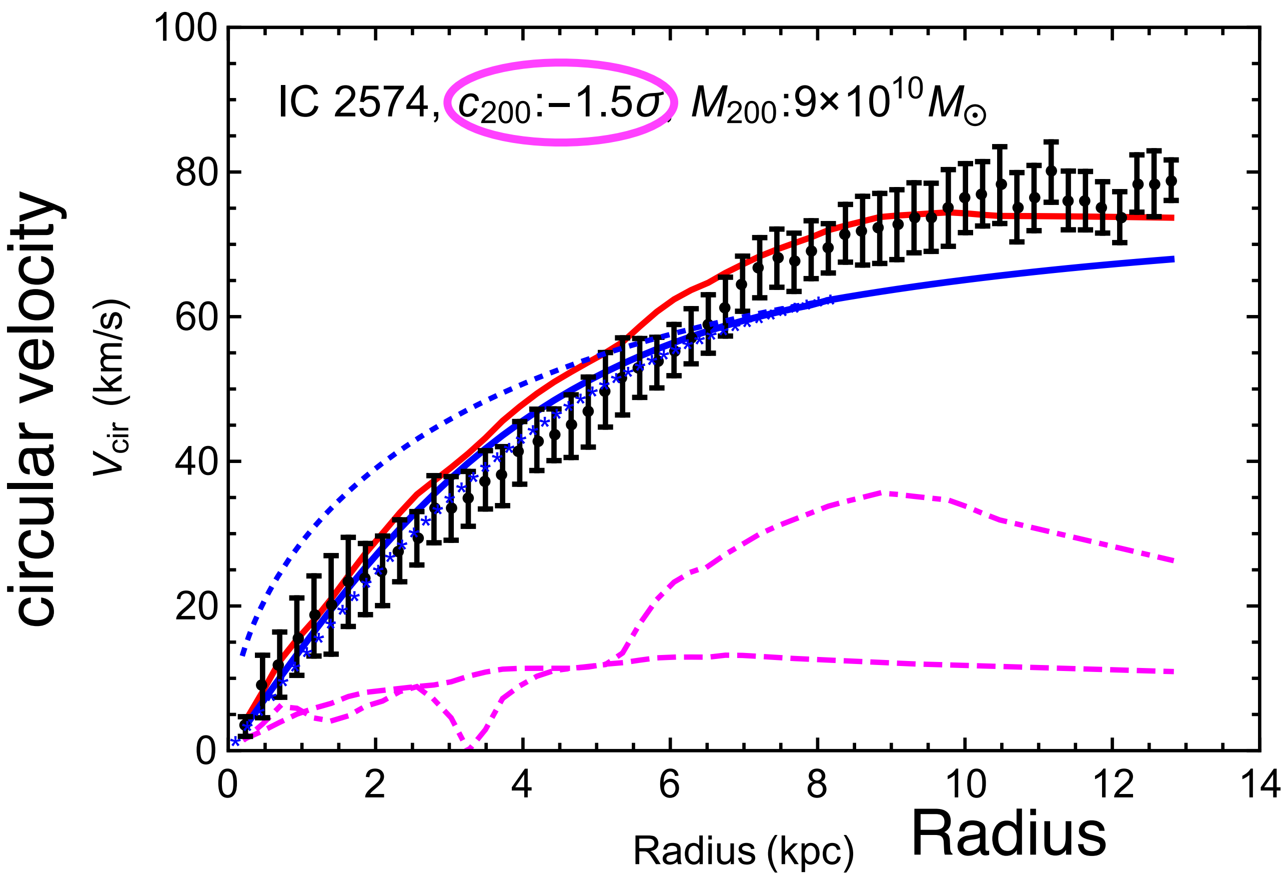
Massive spiral galaxies, **GENERALLY**, make SIDM halos **VIOLATE** the concentration-mass relation

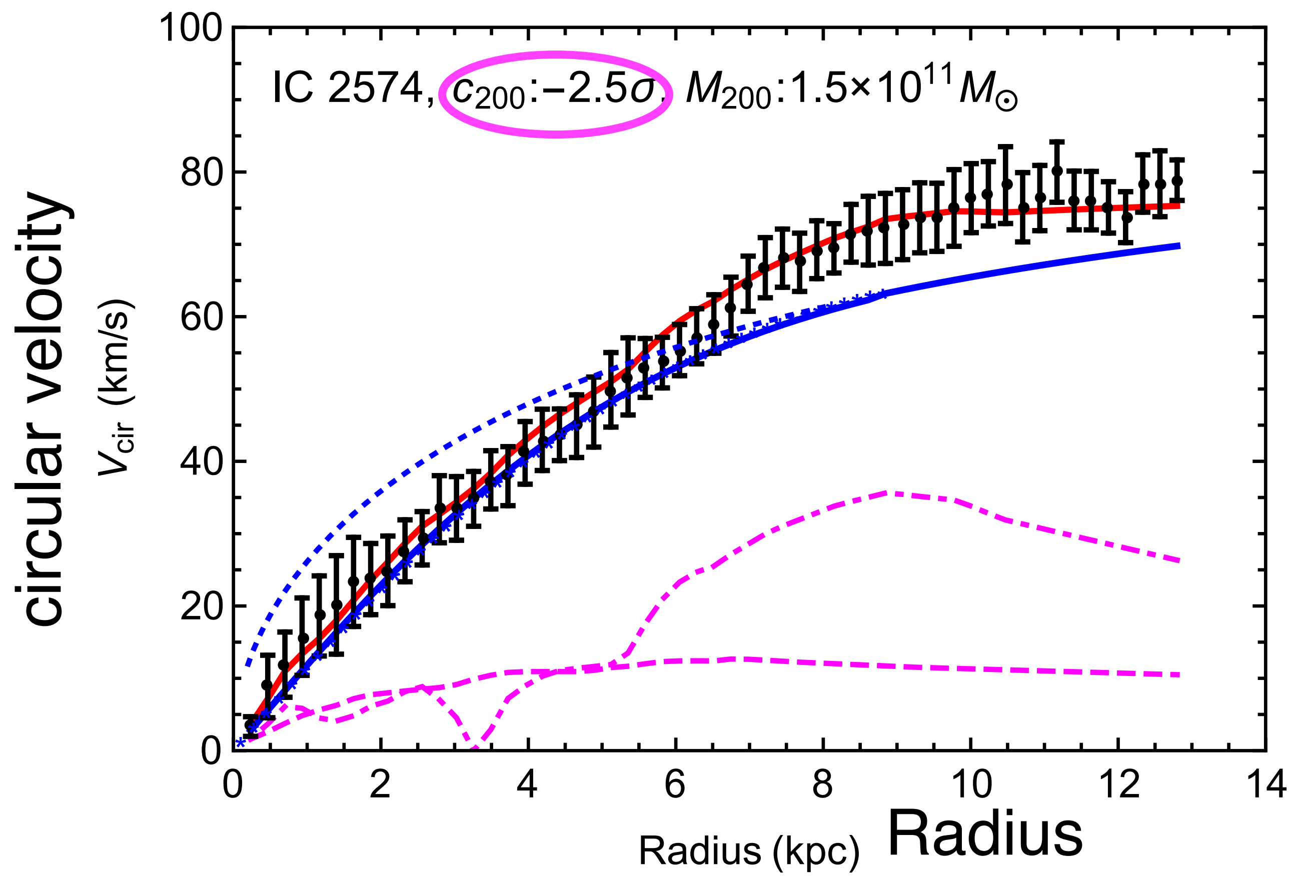


# Case study III

Not only the influence of the baryons, but also the **INTRINSIC SCATTER OF SIDM HALOS** is needed to reproduce the observed diversity



# Highlighted in the New Scientist magazine

THIS WEEK 7 December 2016

## Dark matter that talks to itself could explain galaxy mystery

**Spinning puzzle**
Robert Gendler/Science Photo Library

By **Shannon Hall**

Not all rotation curves look alike – before they reach that characteristic plateau, some rise gradually, and others rise rapidly. But WIMP models struggle to explain this. Also, there has been no direct evidence of WIMPs, despite decades of searching. So Ayuki Kamada at the

# Featured in Physical Review Letters

Featured in Physics | Editors' Suggestion

## Self-Interacting Dark Matter Can Explain Diverse Galactic Rotation Curves

Ayuki Kamada, Manoj Kaplinghat, Andrew B. Pace, and Hai-Bo Yu

Phys. Rev. Lett. **119**, 111102 (2017) – Published 13 September 2017

Physics Synopsis: Self-Interacting Dark Matter Scores Again

Dark matter that interacts with itself provides a better description of the speeds of stars in galaxies than dark matter that doesn't self-interact.

The rotation curves of spiral galaxies exhibit a diversity that has been difficult to understand in the cold dark matter (CDM) paradigm. We show that the self-interacting dark matter (SIDM) model provides excellent fits to the rotation curves of a sample of galaxies with asymptotic velocities in the $25\text{–}300\ \mathrm{km/s}$ range that exemplify the full range of diversity. We assume only the halo concentration-mass relation predicted by the CDM model and a fixed value of the self-interaction cross section. In dark-matter-dominated galaxies, thermalization due to self-interactions creates large cores and reduces dark matter densities. In contrast, thermalization leads to denser and smaller cores in more luminous galaxies and naturally explains the flatness of rotation curves of the highly luminous galaxies at small radii. Our results demonstrate that the impact of the baryons on the SIDM halo profile and the scatter from the assembly history of halos as encoded in the concentration-mass relation can explain the diverse rotation curves of spiral galaxies.

PDF | HTML

# Constraints from galaxy clusters

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

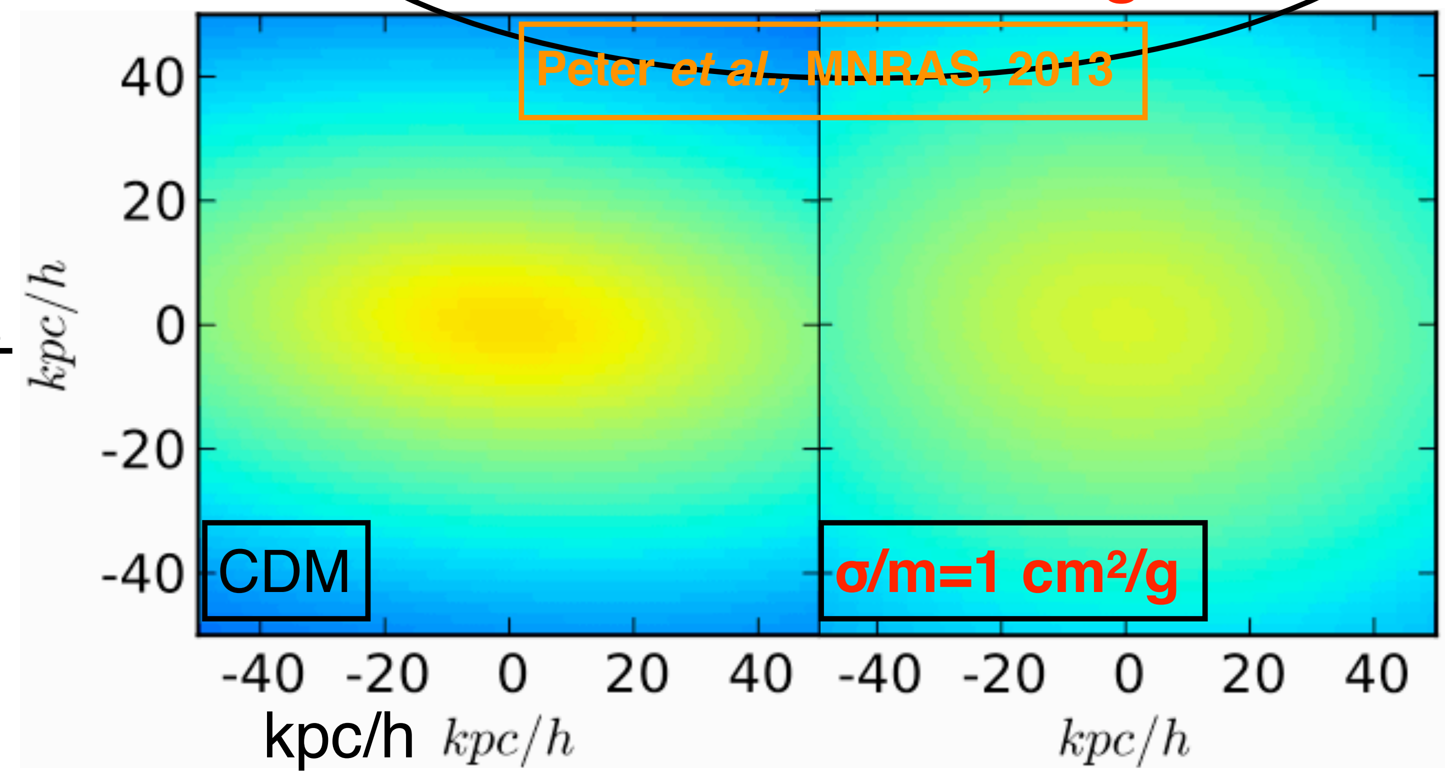
Halo shape - ellipticity
- galaxy cluster MS 2137–23
  (e=0.18@r=70 kpc)

(estimate) $\sigma/m<0.02$ $cm^2/g$

Miralda-Escudé *et al.*, ApJ, 2002

(simulation/l.o.s. effect)
$\sigma/m<1$ $cm^2/g$

Peter *et al.*, MNRAS, 2013




Bullet cluster - transparency
- 1E0657-558

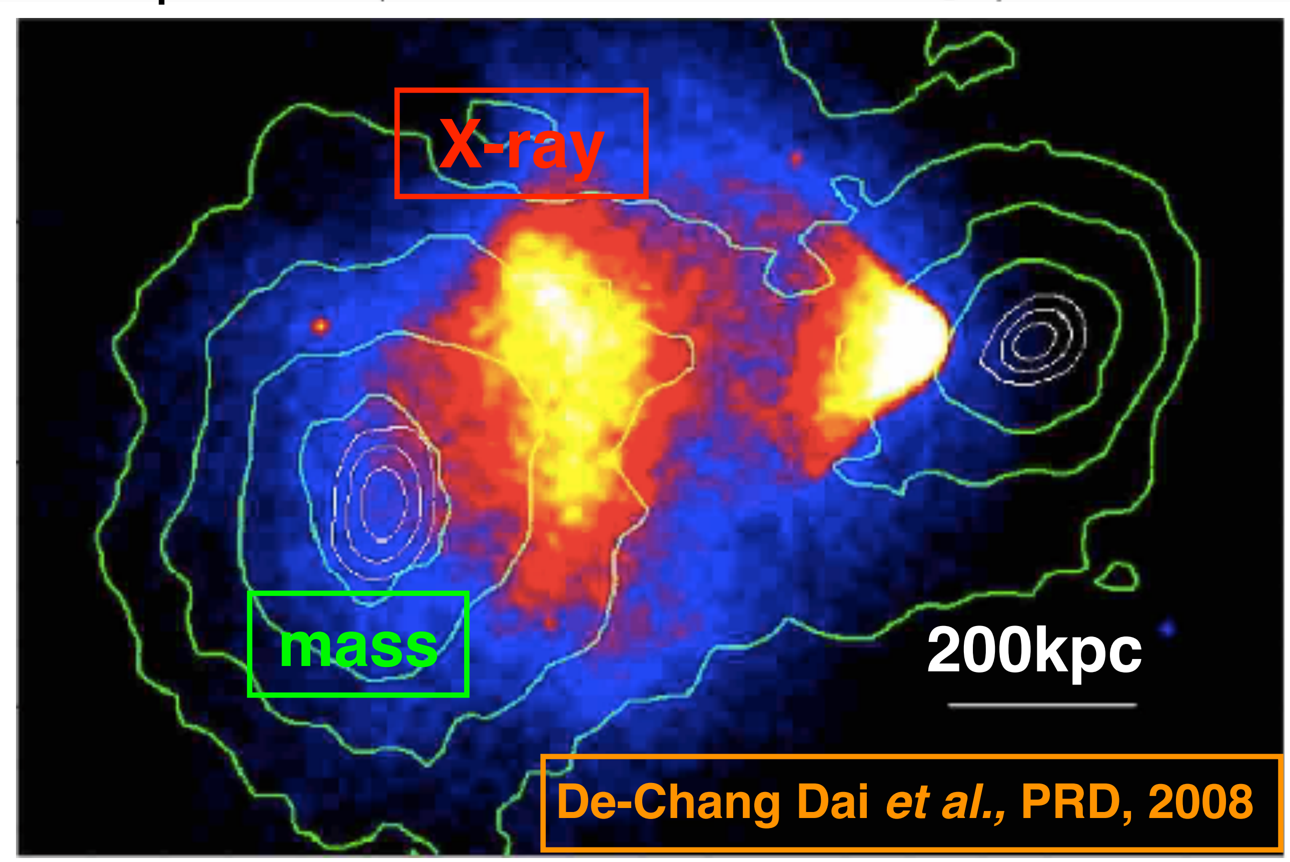
(offset) $\sigma/m<1.25$ $cm^2/g$
(massloss) $\sigma/m<0.7$ $cm^2/g$

Randall *et al.*, ApJ, 2008

- an ensemble (72)

(offset) $\sigma/m<0.47$ $cm^2/g$

Harvey *et al.*, Science, 2015



# Particle physics models I

The constraints from galaxy clusters likely imply that dark matter self-interaction should **DIMINISH WITH INCREASING VELOCITY**, even though not necessarily so far

+ interestingly strong lensing of galaxy clusters may support SIDM with a smaller cross section **$\sigma/m$=0.1 cm²/g**

Tulin *et al.*, PRL, 2012

**velocity-DEPENDENT cross section:**

WIMP dark matter

+ light mediator with

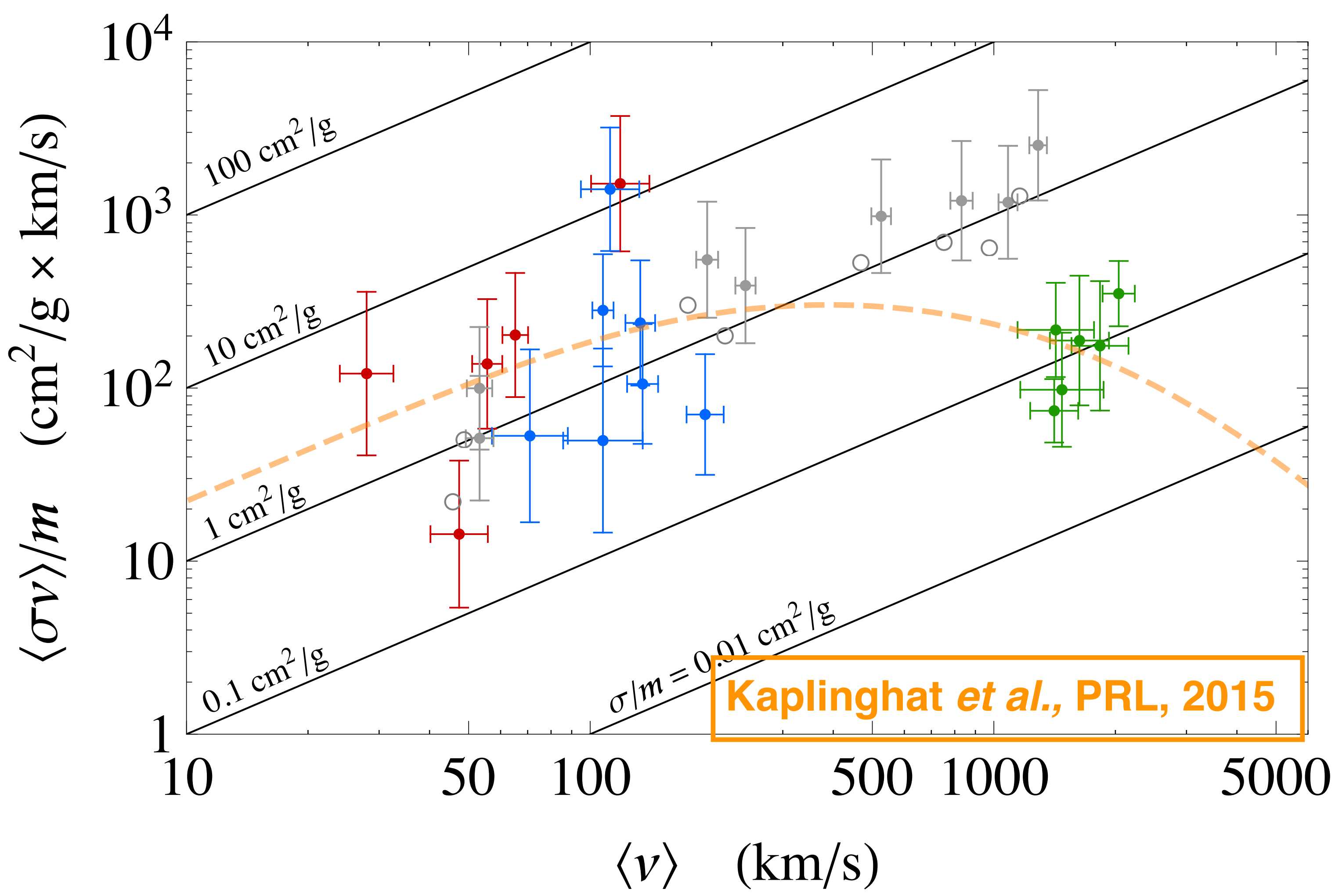
**$m_{med}$~$m_{DM}$ $v_{gal}$/c**

**$\sigma$~1/$m_{med}^2$: const.**

**@ (dwarf) galaxies ($V_{max}$~10-100 km/s)**

**$\sigma$~1/$v^4$: suppressed**

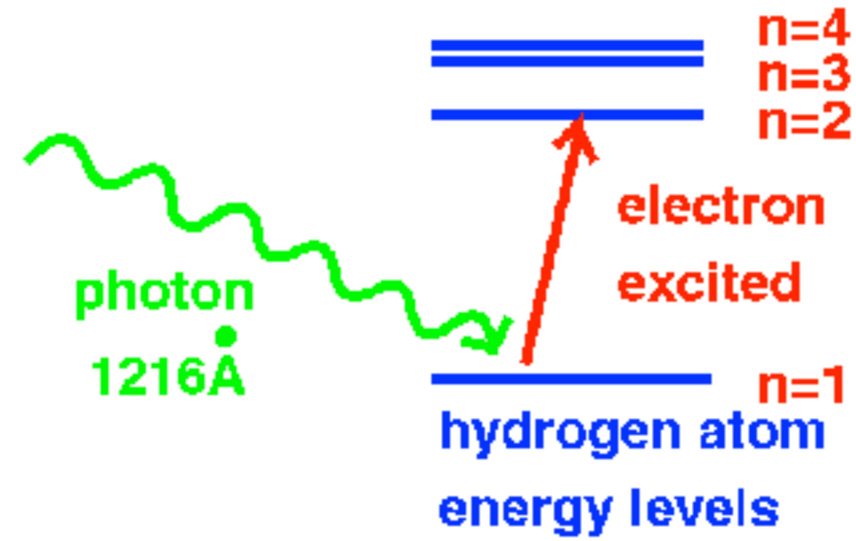
**@ galaxy cluster ($V_{max}$~1000 km/s)**

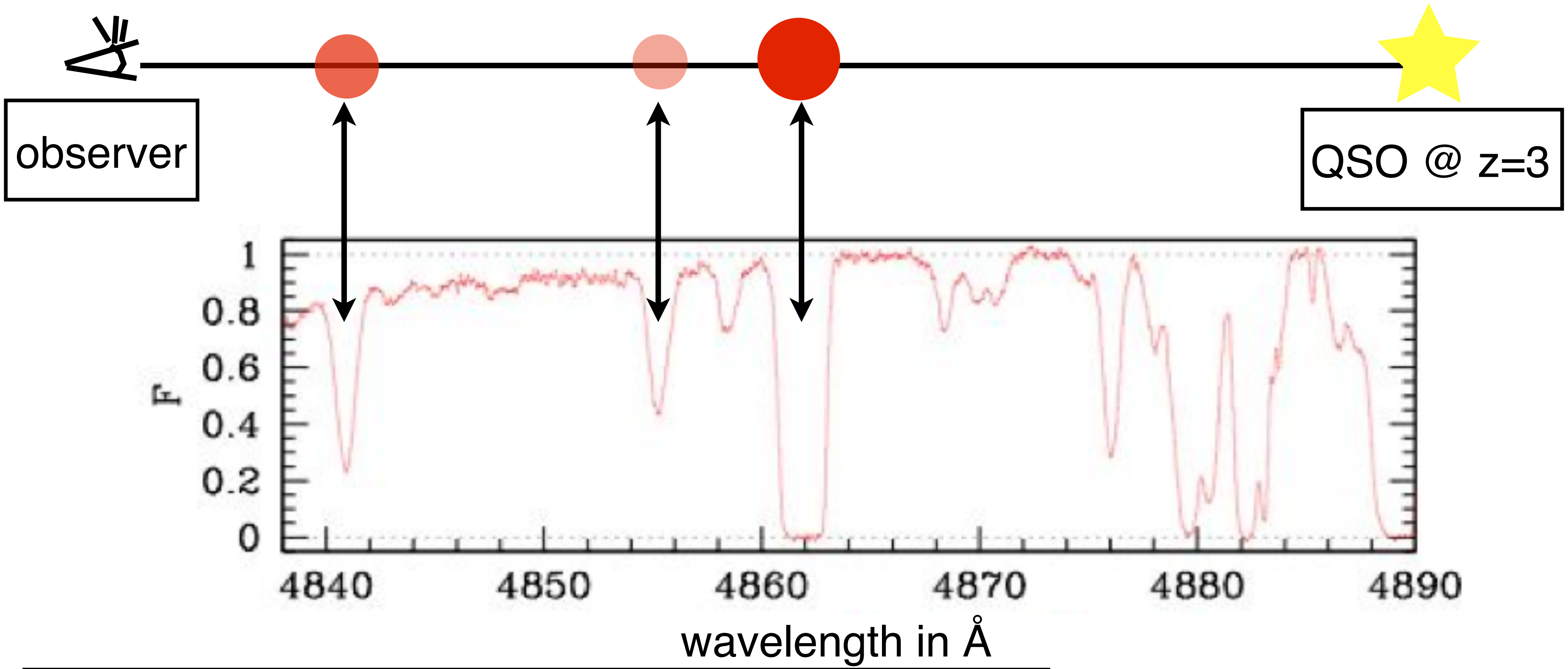



Kaplinghat *et al.*, PRL, 2015

# Lyman-alpha forest as a probe of matter distribution

absorption intensity/frequency
↔ HI distribution along the line-of-sight




normalized flux $F = e^{-\tau}$

optical depth $\tau \propto \left(\frac{\rho_{HI}}{\bar{\rho}}\right)^{\alpha}$ $\alpha \simeq 1.6 - 2.4$

# Mass fraction of the hot component

Decoupling of self-scattering:

$$T_{\rm self} \simeq 1\,{\rm eV} \left(\frac{1\,{\rm cm}^2/{\rm g}}{\sigma_{\rm self}/m_\chi}\right)^{2/3} \left(\frac{m_\chi}{1\,{\rm GeV}}\right)^{1/3} \left(\frac{T_\chi}{T}\right)_{\rm asy}^{-1/3}$$

After the Decoupling of elastic scattering,

$$\int_{t_{\rm self}}^{t_{\rm now}} dt\,\langle\sigma_{\rm semi} v_{\rm rel}\rangle n_\chi \simeq 2\times 10^{-8} \left(\frac{T_{\rm self}}{1\,{\rm eV}}\right) \left(\frac{50\,{\rm MeV}}{T_{\rm fo}}\right)$$

of the whole dark matter particles are boosted though the semi-annihilation → hot component

SM neutrinos: Planck Collaboration, A&A, 2015

$$\Omega_\nu h^2 = 0.1 \frac{\sum m_\nu}{9.4\,{\rm eV}}$$

constraint

- $\sum m_\nu < 0.23\,{\rm eV}$

Light gravitino: Osato, Sekiguchi, Shirasaki, AK, and Yoshida, JCAP, 2016

$$\Omega_{3/2} h^2 = 0.13 \left(\frac{g_{3/2}}{2}\right) \left(\frac{m_{3/2}}{100\,{\rm eV}}\right) \left(\frac{g_{*s3/2}}{90}\right)^{-1}$$

constraint

- $m_{3/2} < 4.7\,{\rm eV}$