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

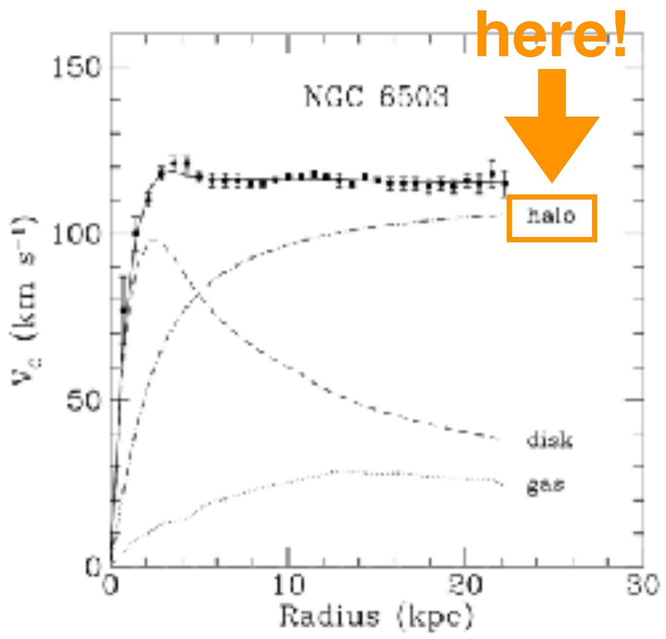
  Z_2 symmetry → pair annihilation

Part 2: Beyond WIMP - a larger symmetry
- Strongly Interacting Massive Particle (SIMP)
  - 3→2 process
  - semi-annihilation

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

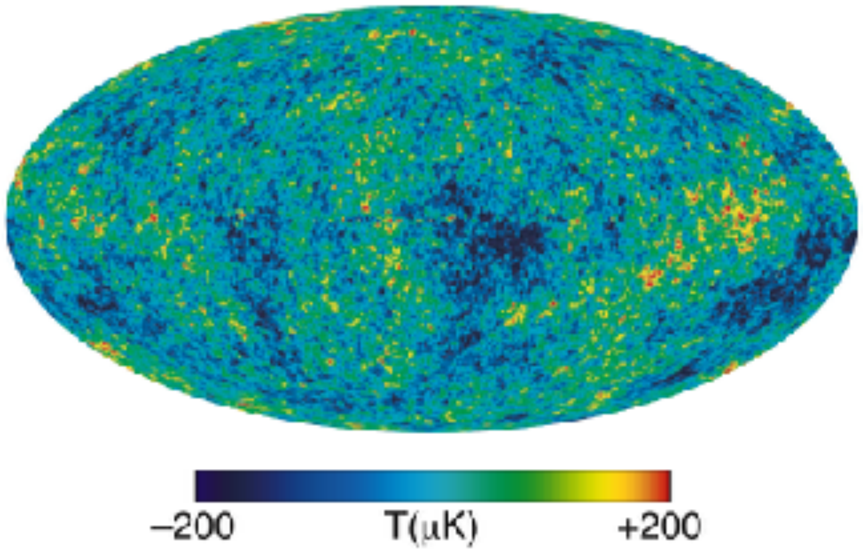
Part 4: Discussion
- implications for the structure formation of the Universe
- other prospects

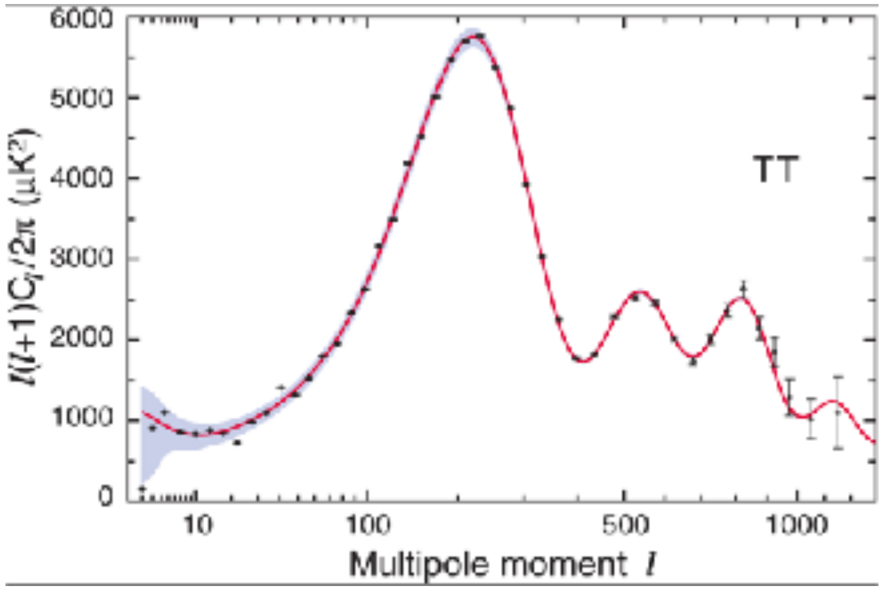
Evidences of dark matter

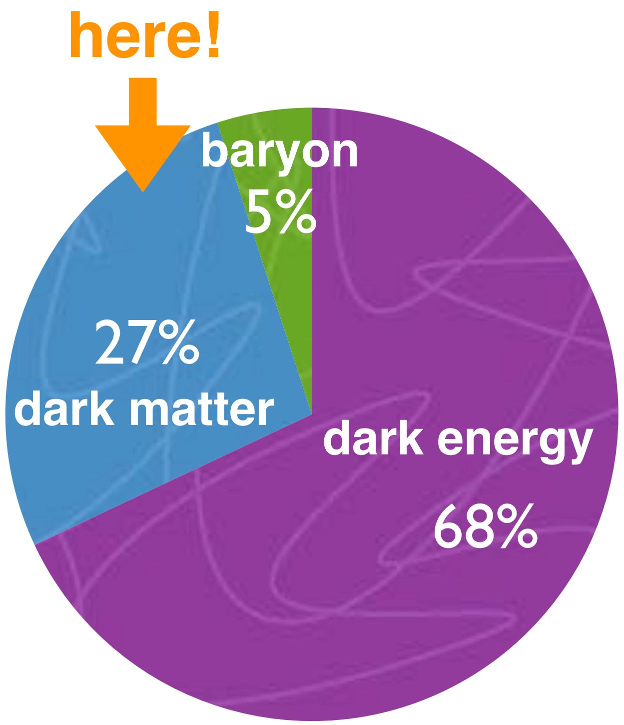


galactic rotation curves

bullet clusters



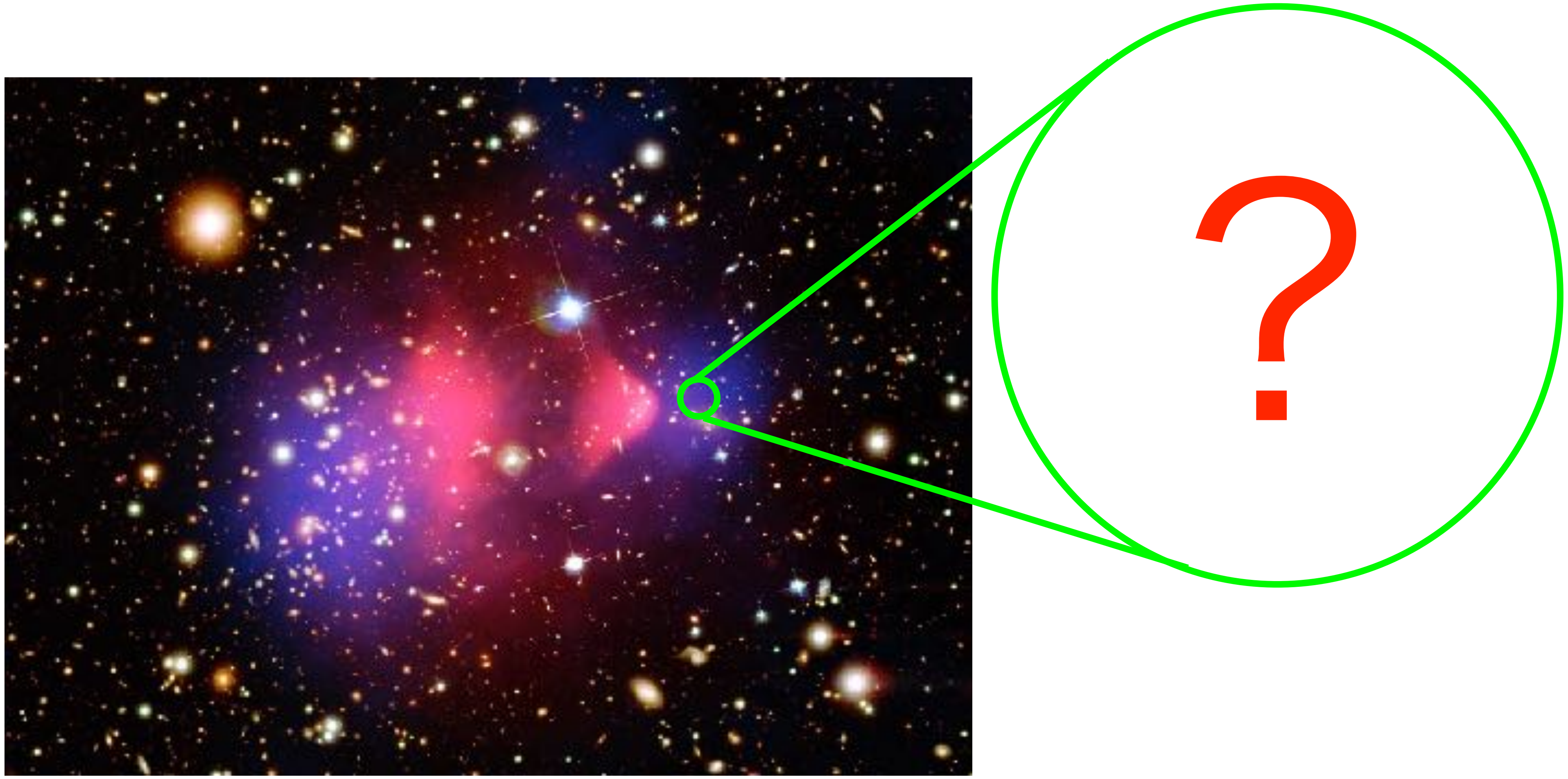




cosmic microwave background (CMB) anisotropies

Observations of the Universe (from dwarf galaxies to CMB) has been suggesting the existence of a new form of matter: dark matter

Identity of dark matter



We do not know the identity, but know **several properties**

Long-lived over the age of the Universe ($\tau_{\rm DM} > 10^{10}\,{\rm yr}$)

Feebly interacting with photons

Not hot

Energy density redshifts as the Universe expands (↔ the dark energy is not diluted):

$$\rho_{\rm DM} \propto (1+z)^3$$

Accounts for about 30% of the present energy density of the Universe: $\Omega_{\rm DM} h^2 = 0.12$

Stability

How to stabilize the dark matter particle

Long-lived massive particles in the standard model (SM):
lightest fermion (ν) - Poincaré symmetry
lightest locally charged particle (e) - gauge symmetry
lightest globally charged particle (p) - accidental symmetry

It took a half century to understand it

Minimal phenomenological approach: new Z_2 **symmetry** under which SM particles: **even**, DM particle: **odd**

Another half century?

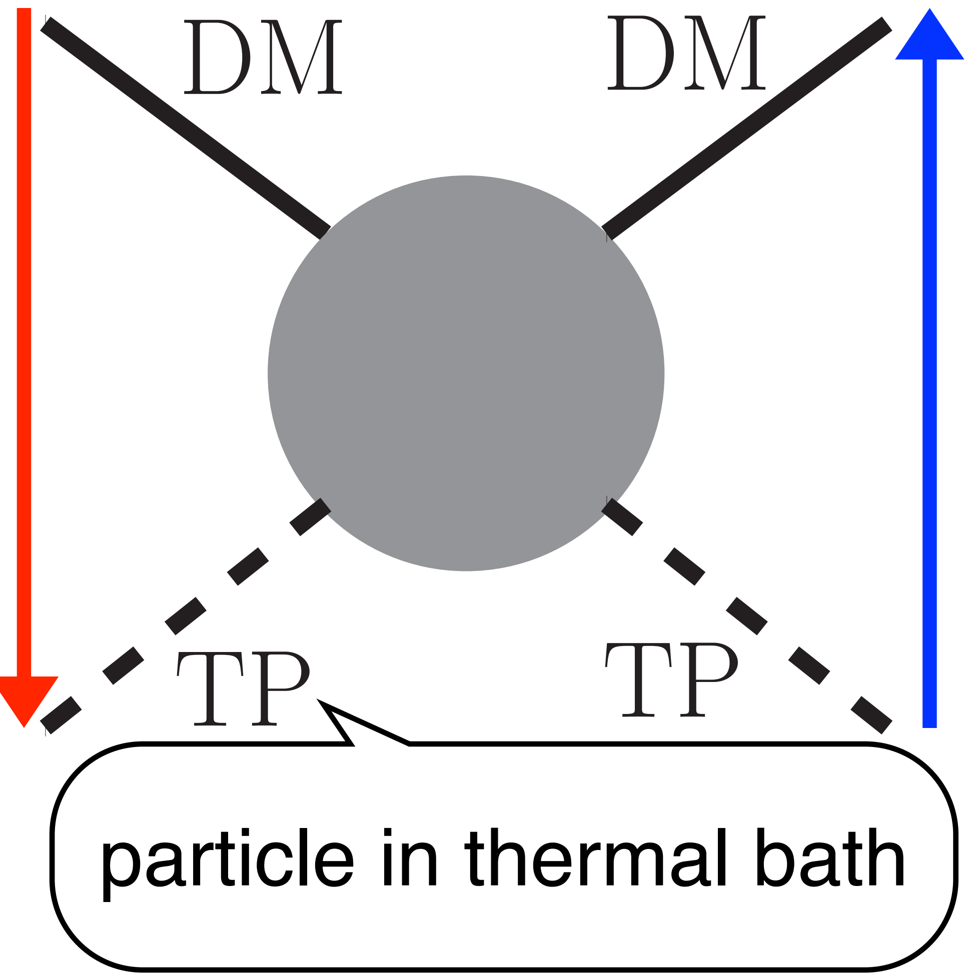
Quantum gravity violates any global symmetry?

Kallosh *et al.*, PRD, 1995

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



particle in thermal bath

: 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:

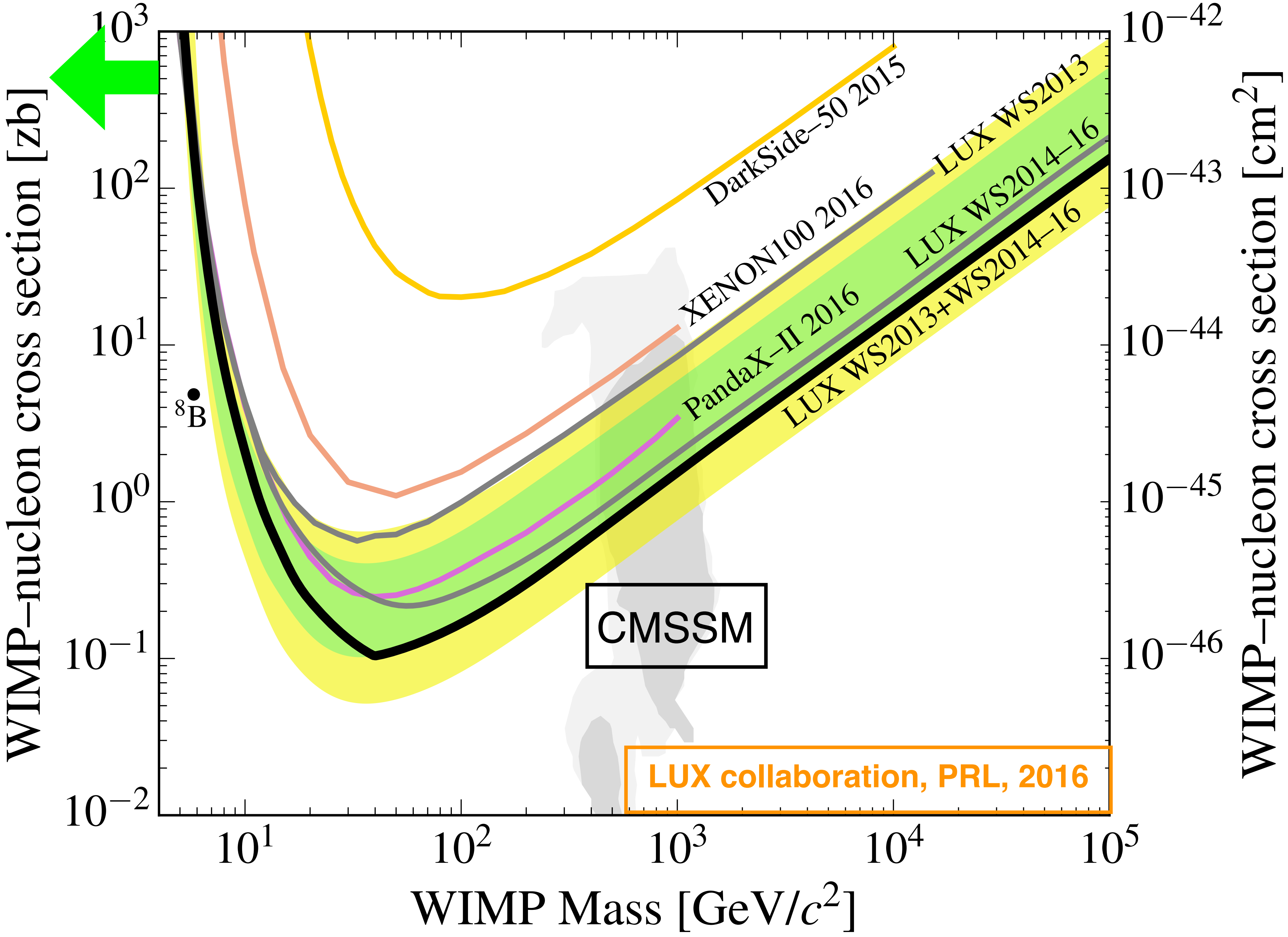
$$\dot{n}_{\mathrm{DM}} + 3Hn_{\mathrm{DM}} = -\langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle \left(n_{\mathrm{DM}}^2 - n_{\mathrm{DM}}^{\mathrm{eq}\,2} \right)$$

$\Omega_\chi h^2 = \Omega_{\mathrm{DM}} h^2$
w/ electroweak scale annihilation cross section:
$\langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle \simeq 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$

Weakly Interacting Massive Particle (WIMP)!!

Direct detection

too small recoil energy



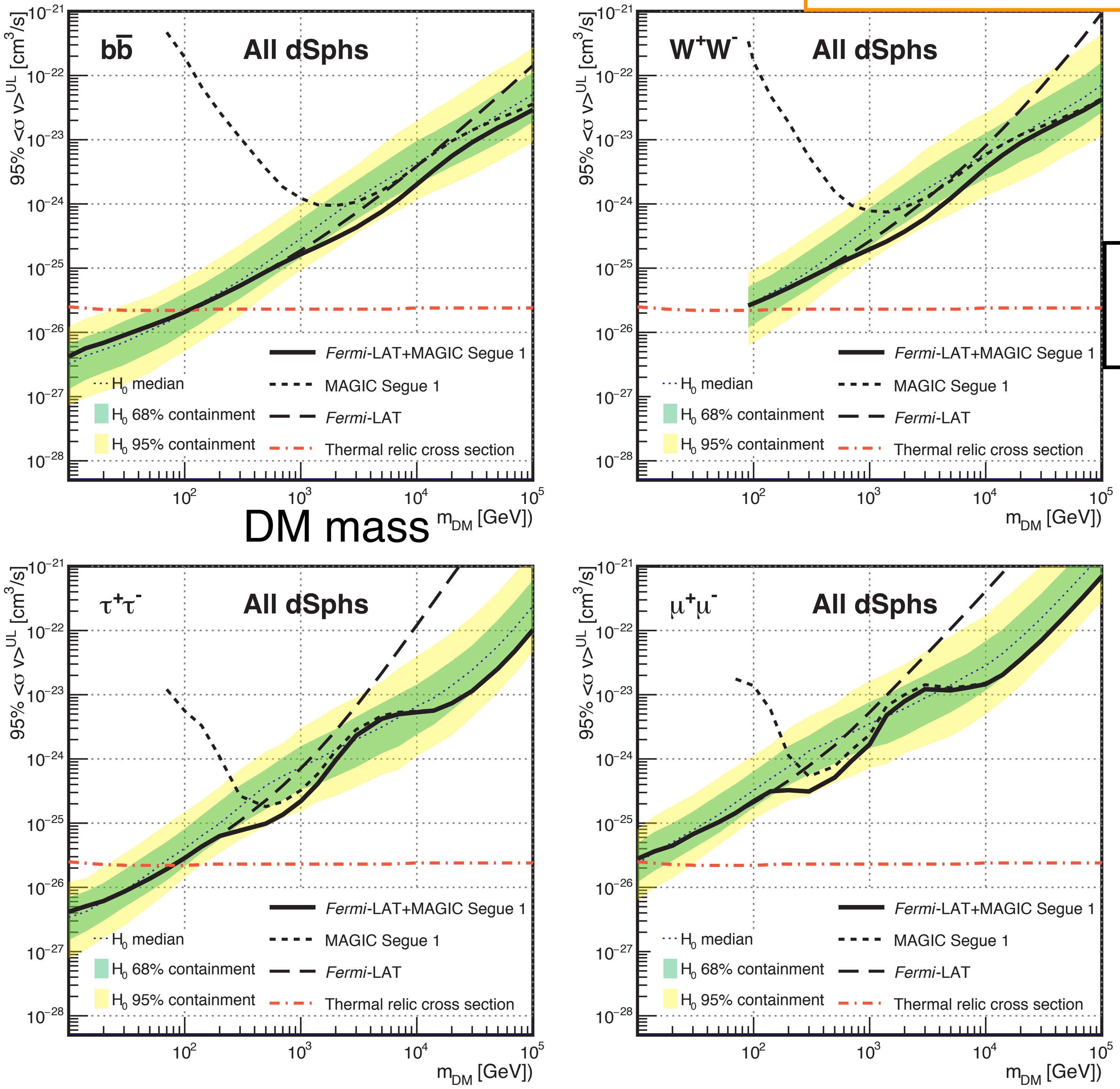
LUX collaboration, PRL, 2016

SUSY WIMPs have been tightly constrained

Indirect detection

Magic and Fermi-LAT Collaborations, JCAP, 2016

annihilation cross section



DM mass

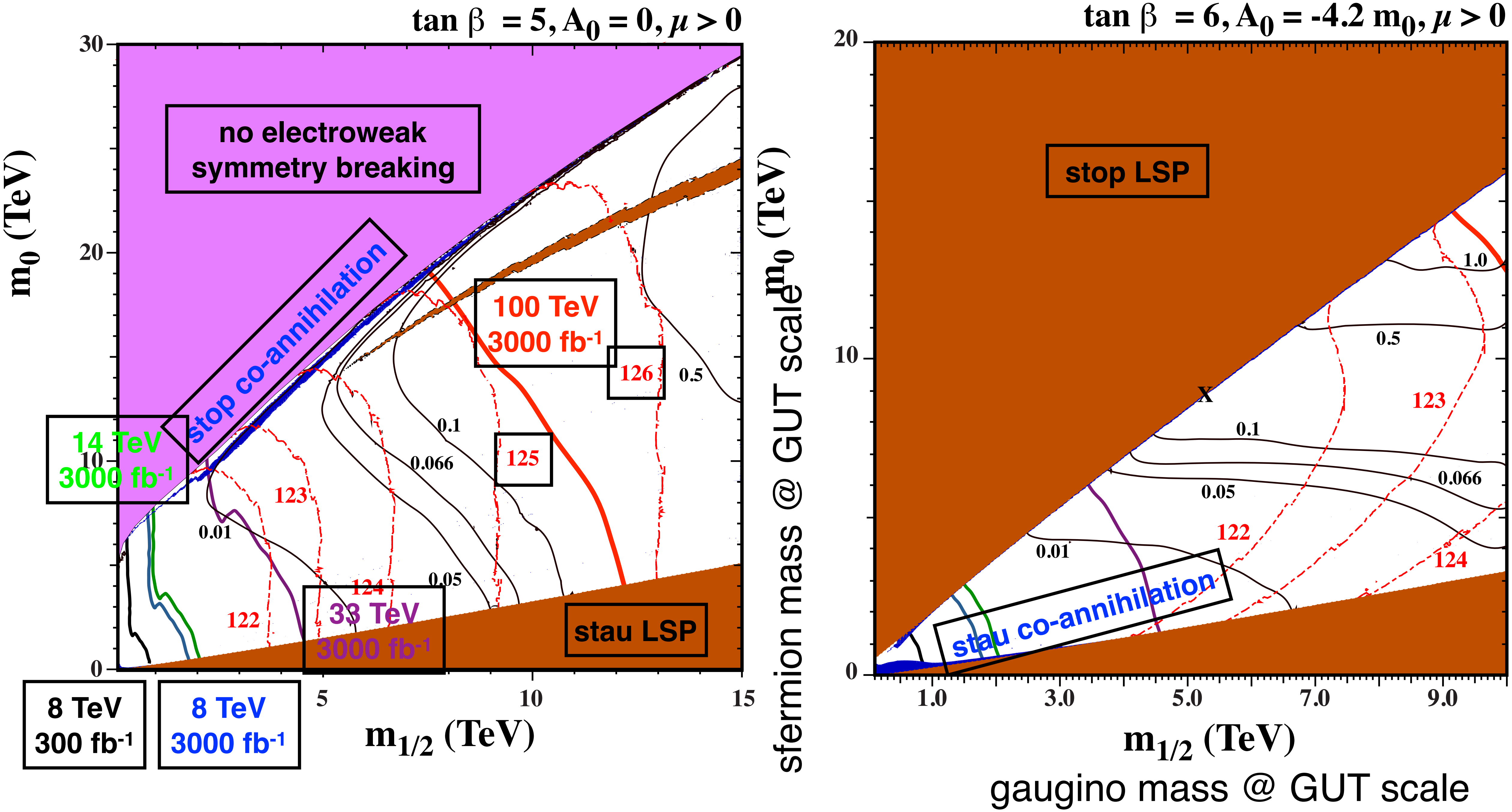
canonical cross section
↔ thermal relic

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

Collider experiment

CMSSM

Ellis, Evans, Mustafayev, Nagata, Olive, Eur. Phys. J., 2016



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

A larger symmetry for the stability

Strongly Interaction 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

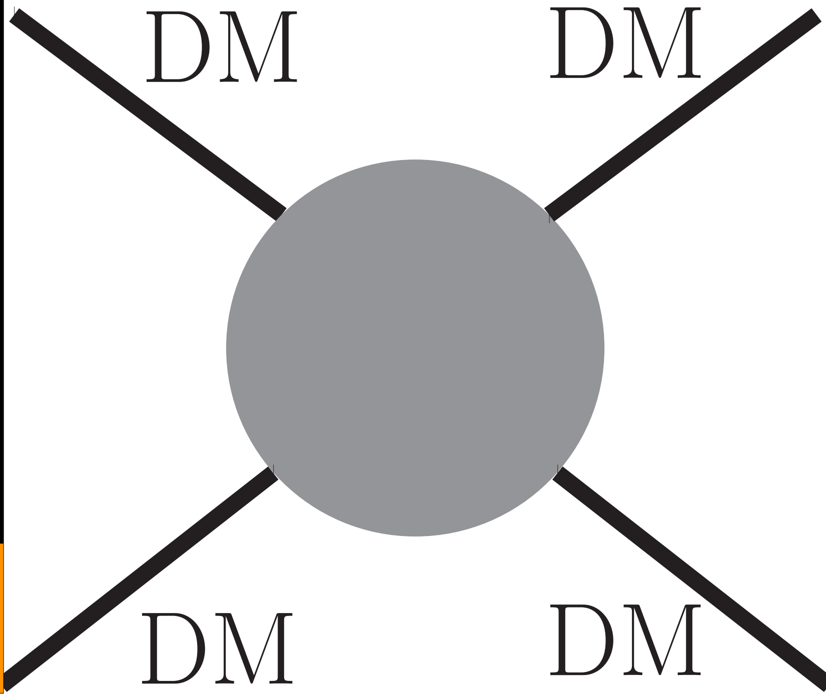
Hochberg *et al.*, PRL, 2015

Unbroken flavor symmetry → the stability of pions
Two parameters in pion phenomenology -
m_π: pion mass & f_π: 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

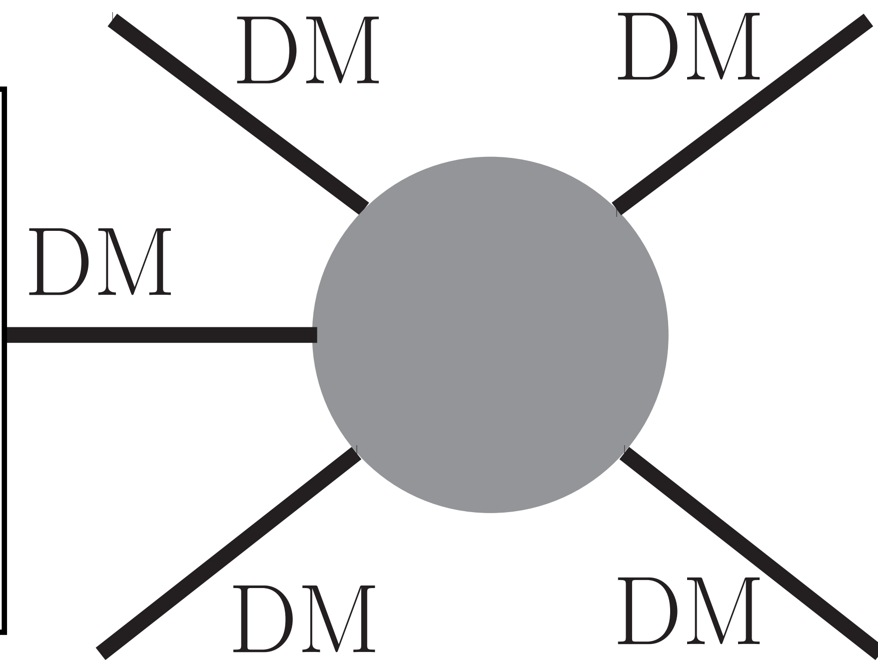
Witten, Nucl. Phys. B, 1983

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

3→2 process:

$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = -\langle\sigma_{3\to2}v_{\rm rel}^2\rangle\left(n_{\rm DM}^3 - n_{\rm DM}^2 n_{\rm DM}^{\rm eq}\right)$$

$\langle\sigma_{3\to2}v_{\rm rel}^2\rangle \sim \frac{m_\pi^5}{f_\pi^{10}}$: 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:

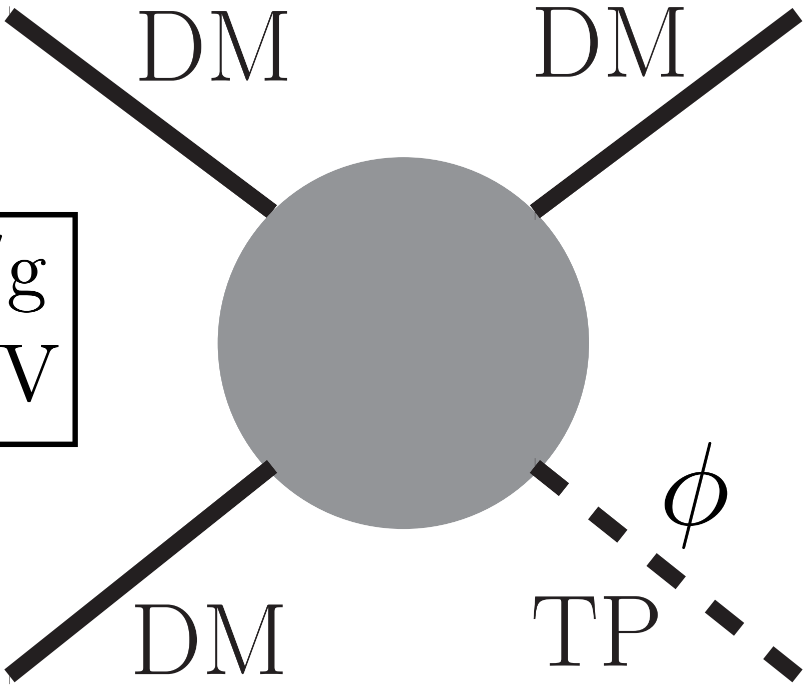
$$\frac{g_H^2}{32\pi^2}\left(\frac{\phi}{f}+\theta_H\right)H^i{}_{\mu\nu}\widetilde{H}^{i\mu\nu}$$

AK, Hyungjin Kim, and Sekiguchi, PRD, 2017

semi-annihilation:

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

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



improving the perturbativity of the non-linear sigma model:
$m_\pi\simeq\Lambda_{\rm cut}\rightarrow m_\pi<\Lambda_{\rm cut}$
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

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

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:

$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = -\langle\sigma_{3\to2}v_{\rm rel}^2\rangle\left(n_{\rm DM}^3 - n_{\rm DM}^2 n_{\rm DM}^{\rm eq}\right)$$

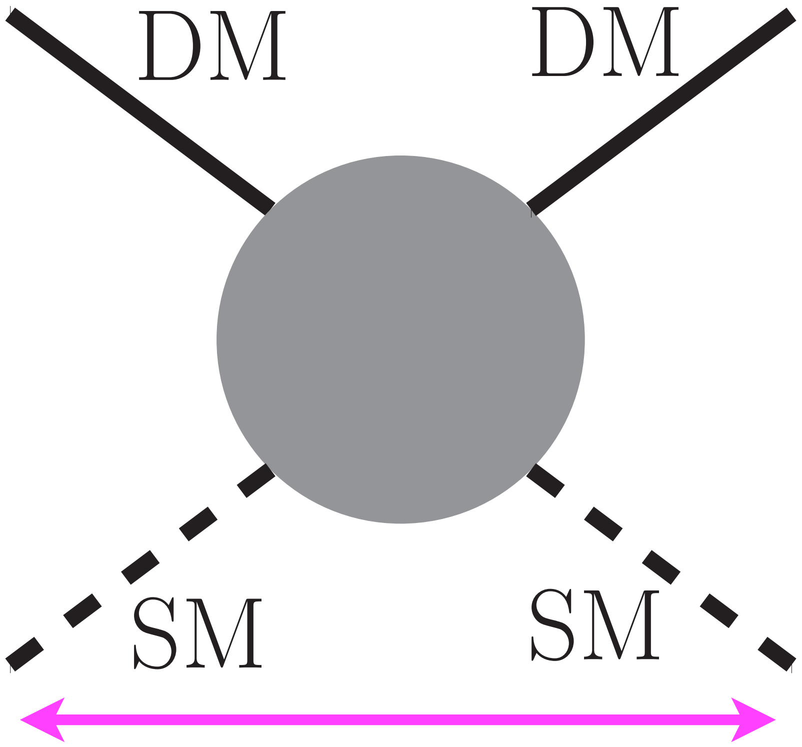
semi-annihilation:

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

WHOSE temperature is T ?

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

Kinetic interaction of WIMPs

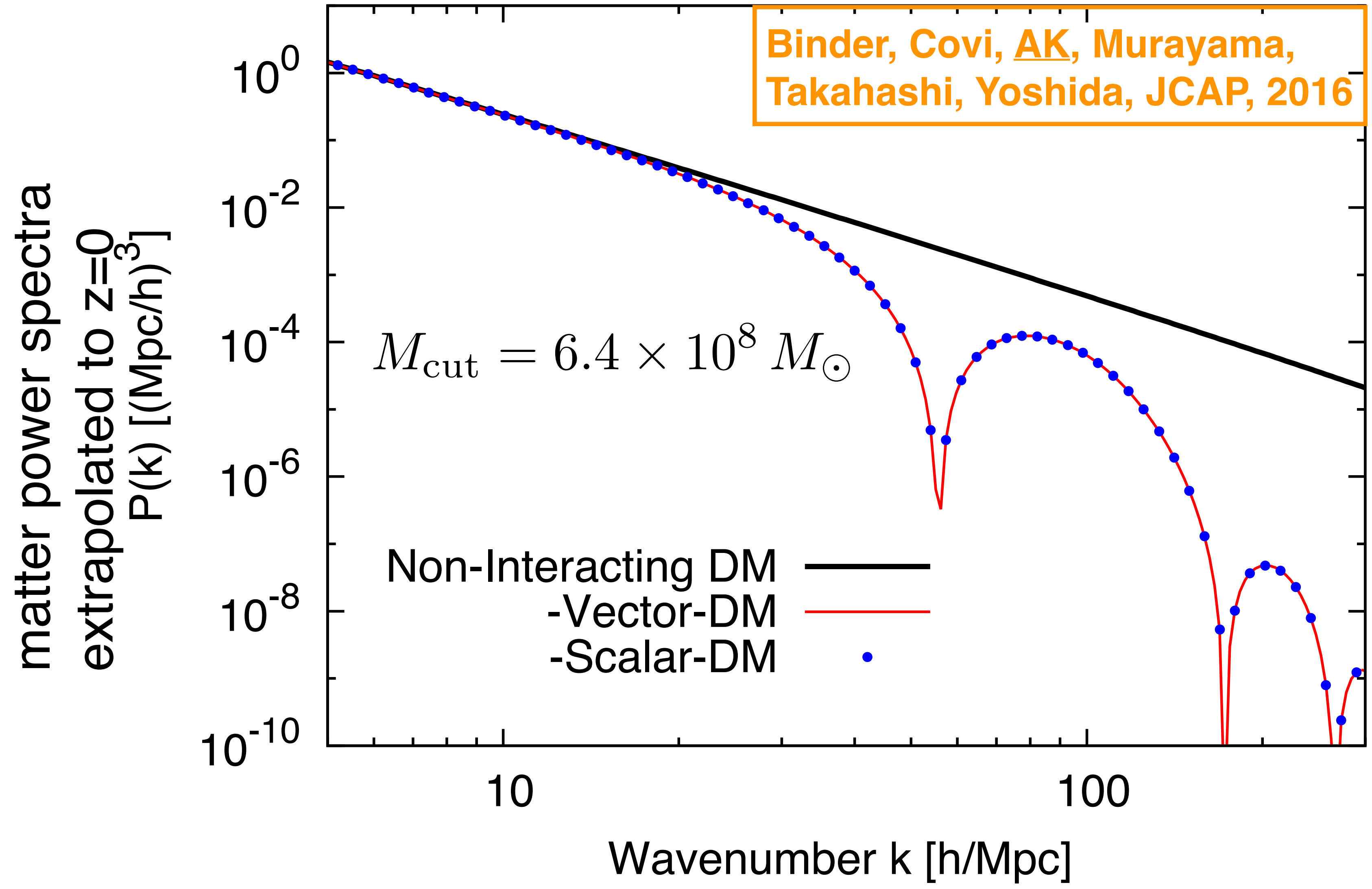


crossing symmetry
kinetic interaction
↔ chemical interaction

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

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

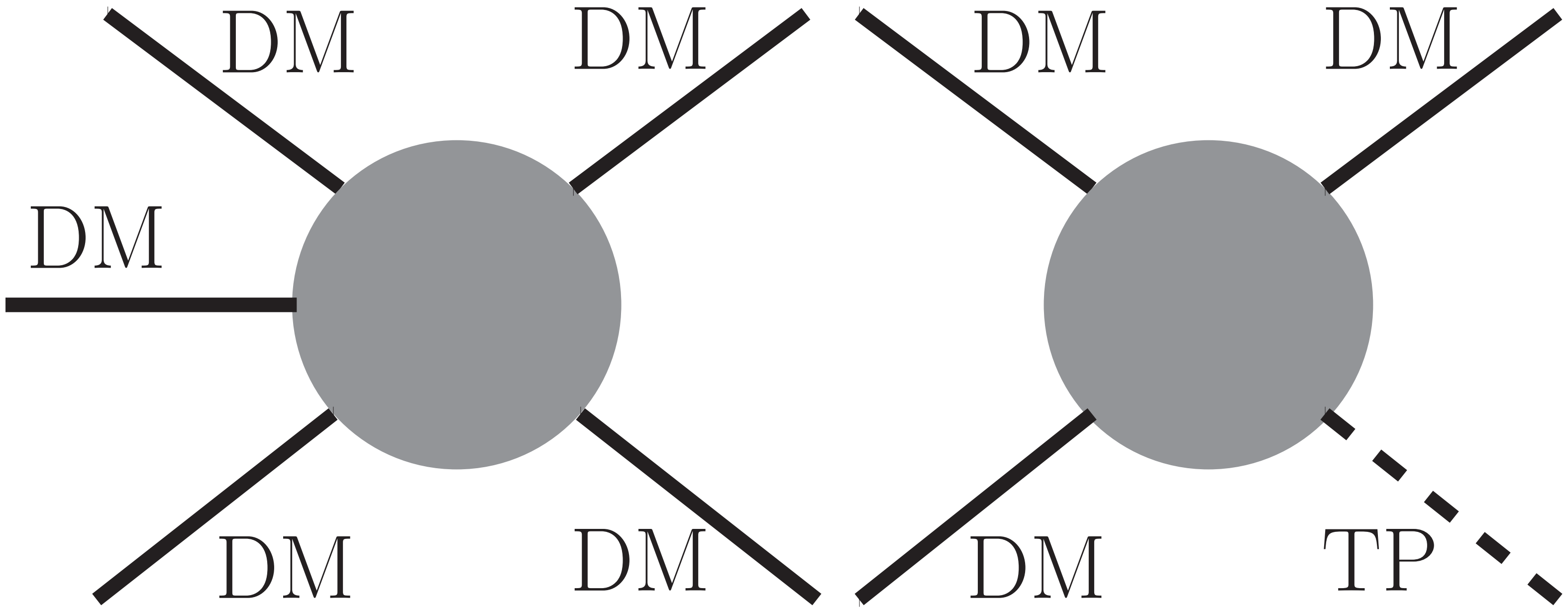
→ minimum mass of protohalo



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

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 $n_{\rm DM}$ & $T_{\rm DM}$

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

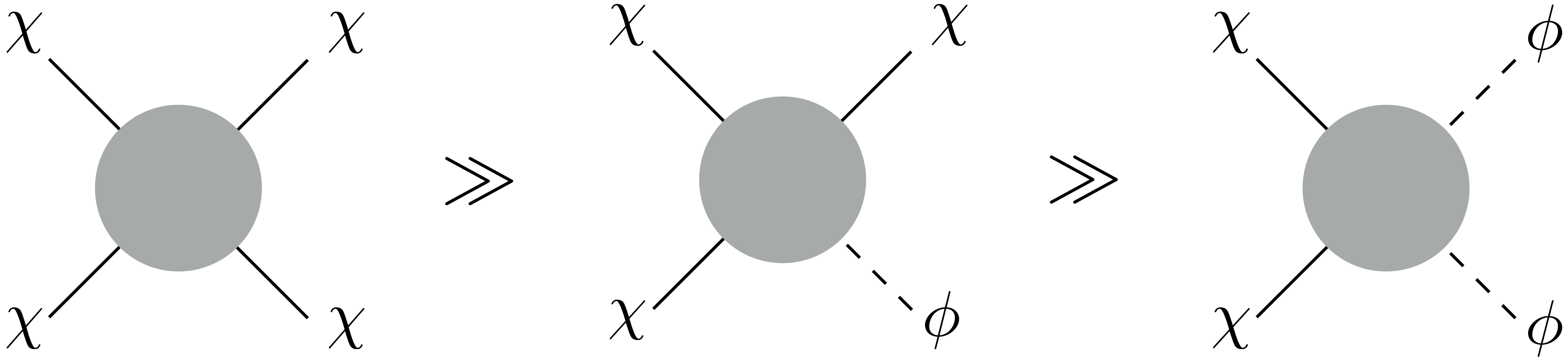
Carlson *et al.*, APJ, 1992

→ $T_{\rm DM} \propto 1/\ln a$ (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

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

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

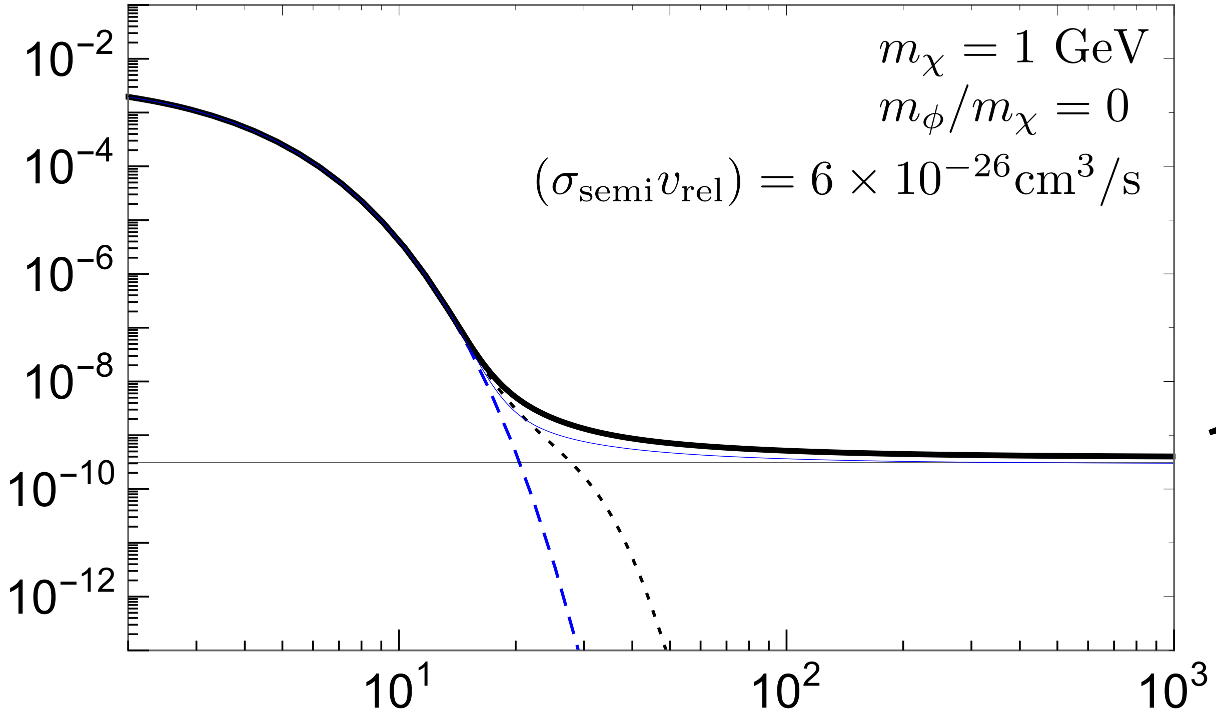
heating through the semi-annihilation

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

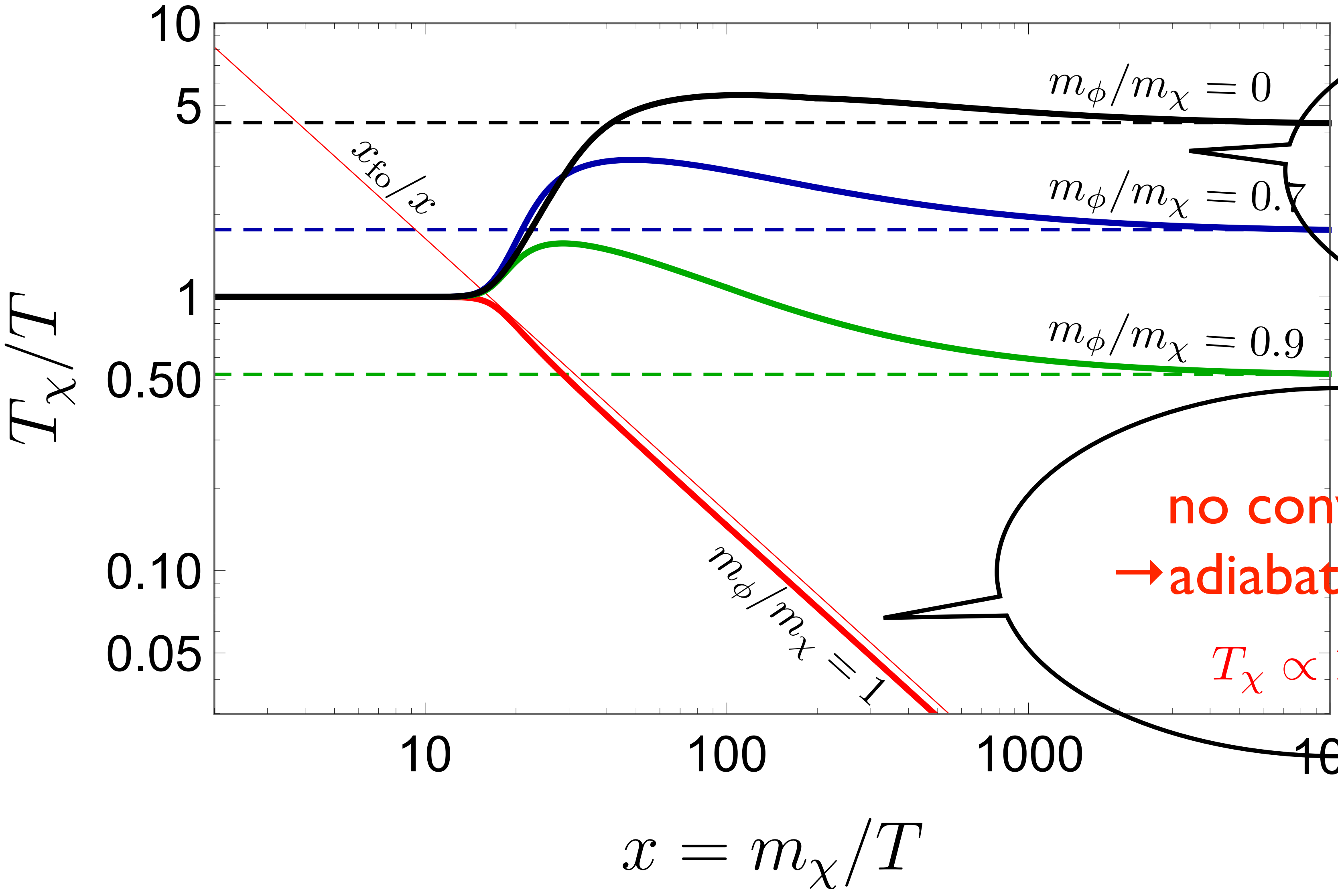
$$\bar\lambda = \frac{xs\langle(\Delta E/m_\chi)\sigma_{\rm inv}v_{\rm rel}\rangle_{T_\chi,T_\phi=T_\chi}}{H}\frac{n_\phi^{\rm eq}(T_\phi=T_\chi)}{n_\chi^{\rm eq}(T_\chi)}\,, \quad \mathcal{K}(x_\chi,x) \equiv \frac{n_\phi^{\rm eq}(T_\phi=T)}{n_\phi^{\rm eq}(T_\phi=T_\chi)}\frac{\langle\Delta E\,\sigma_{\rm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

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

Co-evolution of the temperature and number density

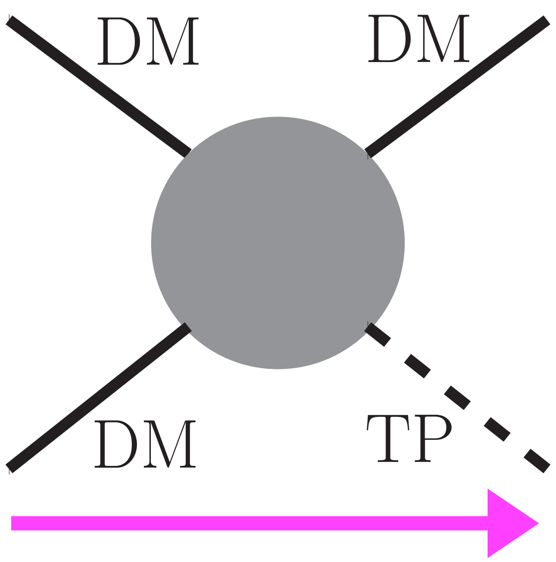


~30% difference between the co-evolution and $T_\chi = T \propto 1/a$

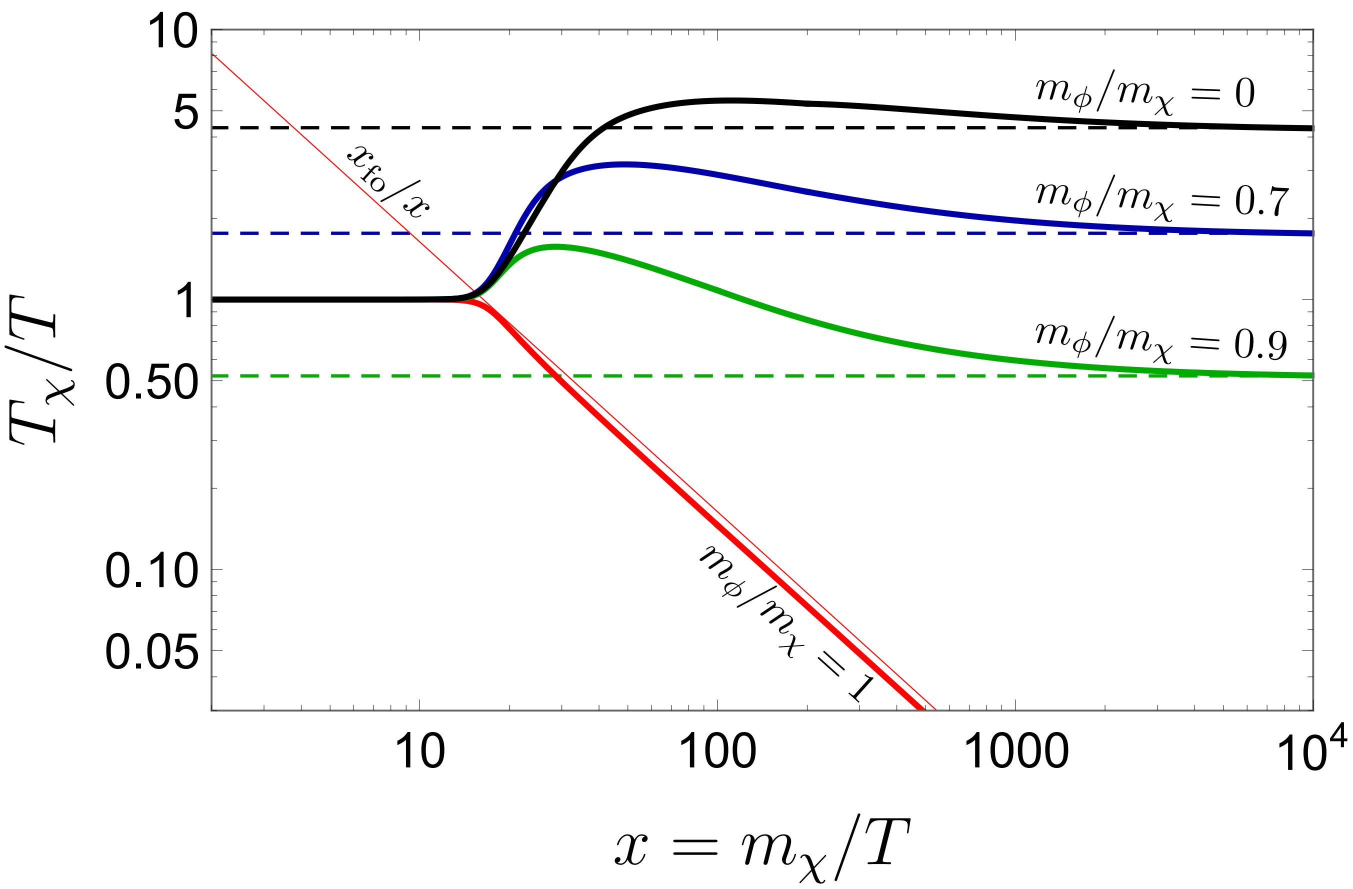


mass deficit converted into the kinetic energy → heating $T_\chi \propto 1/a$

no conversion →adiabatic cooling $T_\chi \propto 1/a^2$



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 $m_\phi = m_\chi$,

$$k_{\rm J} = 2\times 10^6\,{\rm Mpc}^{-1}\left(\frac{m_\chi}{1\,{\rm GeV}}\right)^{1/2}\left(\frac{T_{\rm fo}}{50\,{\rm GeV}}\right)^{1/2}$$

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)

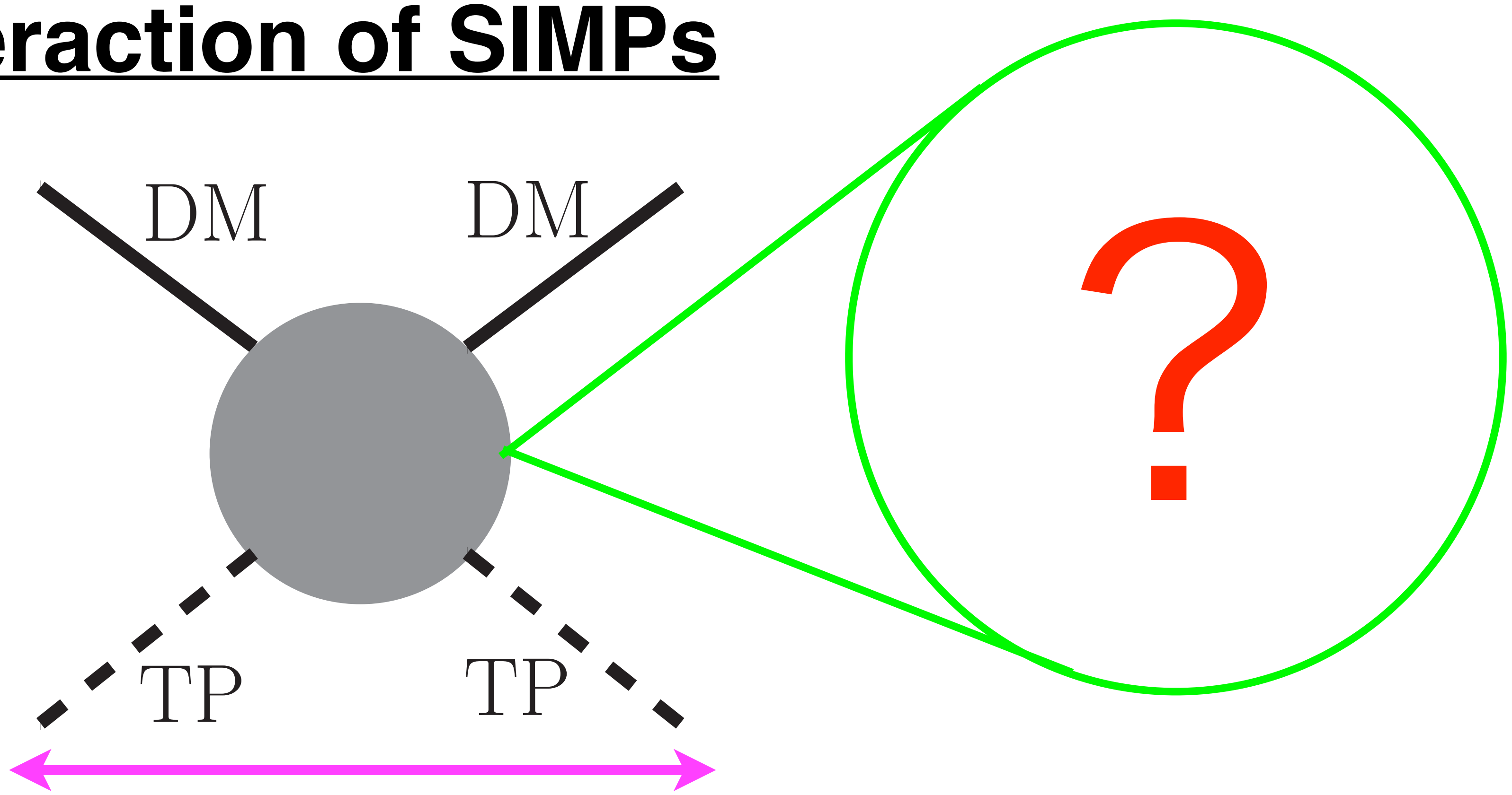
Sub-GeV pion mass and comparable pion decay constant/ electroweak scale ALP decay constant
→ correct relic abundance through the 3→2 process/semi-annihilation and large cross section to produce sizable halo cores

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

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**

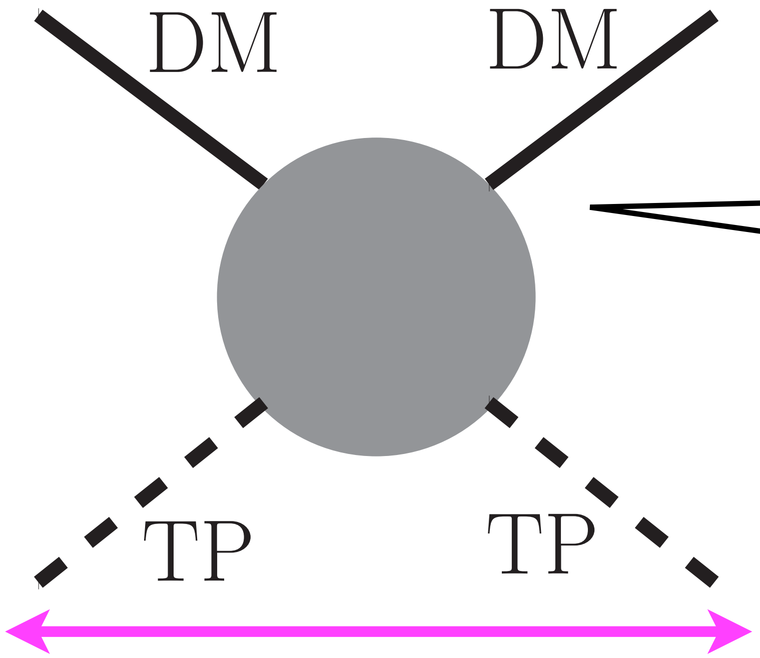
Higgs portal: introducing a hidden Higgs, VEV of which provides a mass to quarks (and pions)

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 $H = \mathrm{SU}(N_f)_V$:

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

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

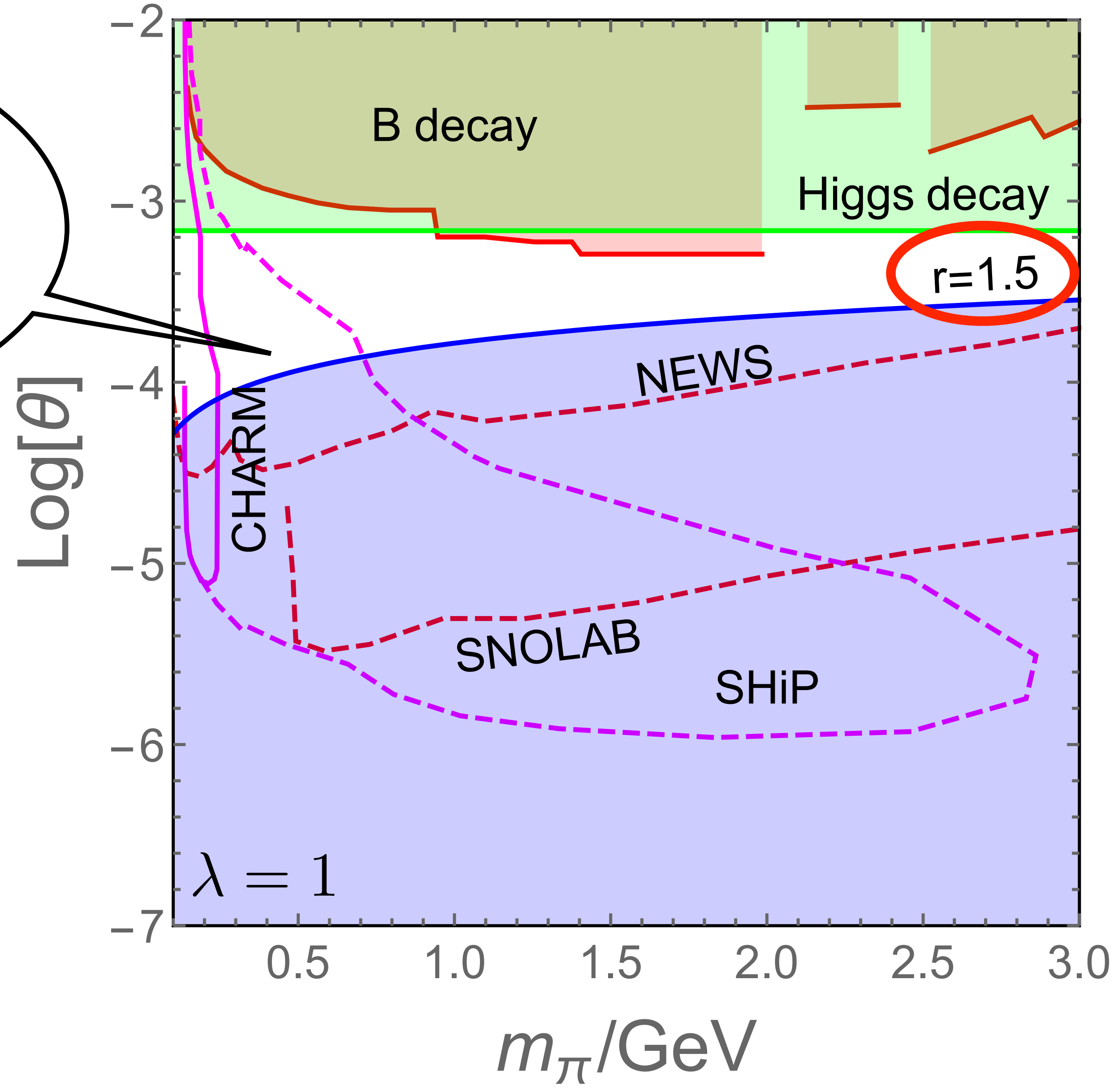
$$\begin{aligned}\mathcal{L}_{\rm CP} = {} & \frac{m_\pi^2}{4N_f^2 f^2}\left(\pi^a\right)^2 \phi^2 - \frac{1}{6f_\pi^2} r_{abcd}\left(\partial_\mu \pi^a\right)\left(\partial^\mu \pi^b\right)\pi^c\pi^d \\ & + \frac{m_\pi^2}{6N_f f_\pi f} d_{abc}\pi^a\pi^b\pi^c\phi + \frac{m_\pi^2}{12 f_\pi^2} c_{abcd}\pi^a\pi^b\pi^c\pi^d\end{aligned}$$

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

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



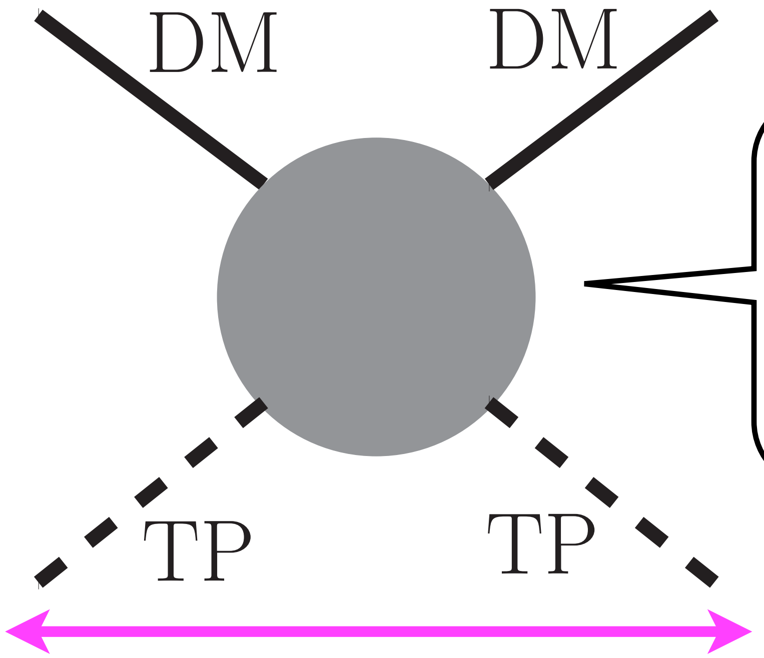
The quark mass term respects a vector-like symmetry that is unbroken even after the chiral condensation (↔ subscript of i):

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

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 (ϕ):
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

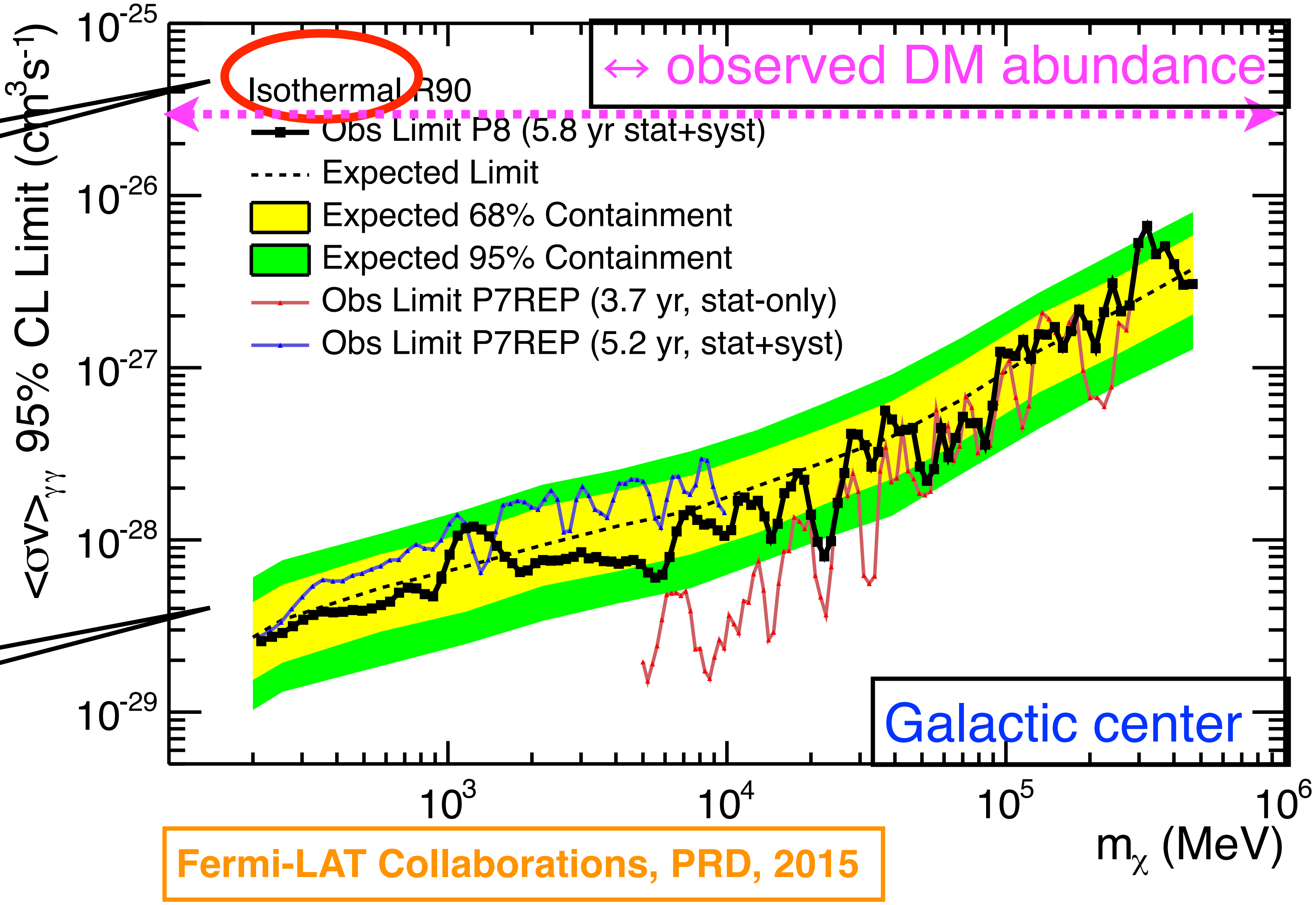
Constraints on semi-annihilation to an ALP

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:
$\langle \sigma_{\rm semi} v_{\rm rel} \rangle = \langle \sigma_{\rm semi} v_{\rm rel} \rangle_{\rm fo} \, (v_{\rm rel}/v_{\rm rel,\,fo})$ where
$v_{\rm rel,\,fo} \simeq 0.5 \simeq 2 \times 10^5 \, {\rm km/s}$

SIDM follows the isothermal profile



↔ observed DM abundance

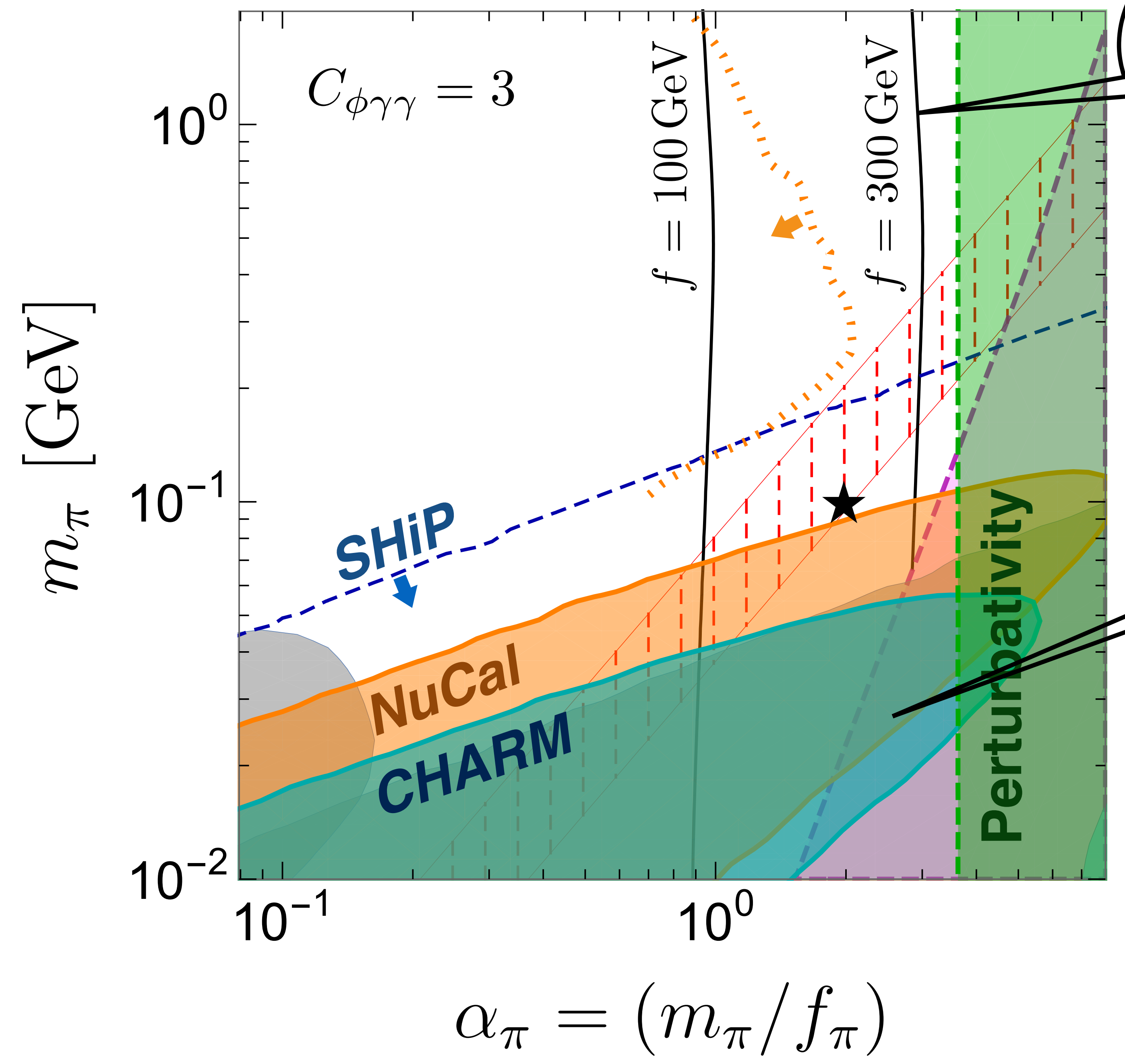
Galactic center

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

Fermi-LAT Collaborations, PRD, 2015

Viable parameter region in an ALP-portal model

$N_c = 3,\ \ N_f = 4,\ \ \theta_H = 0$



$\pi\pi \to \pi\phi$ reproduces the observed DM abundance

$\pi\pi\pi \to \pi\pi$ dominates the freeze-out

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:

adiabatic cooling

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

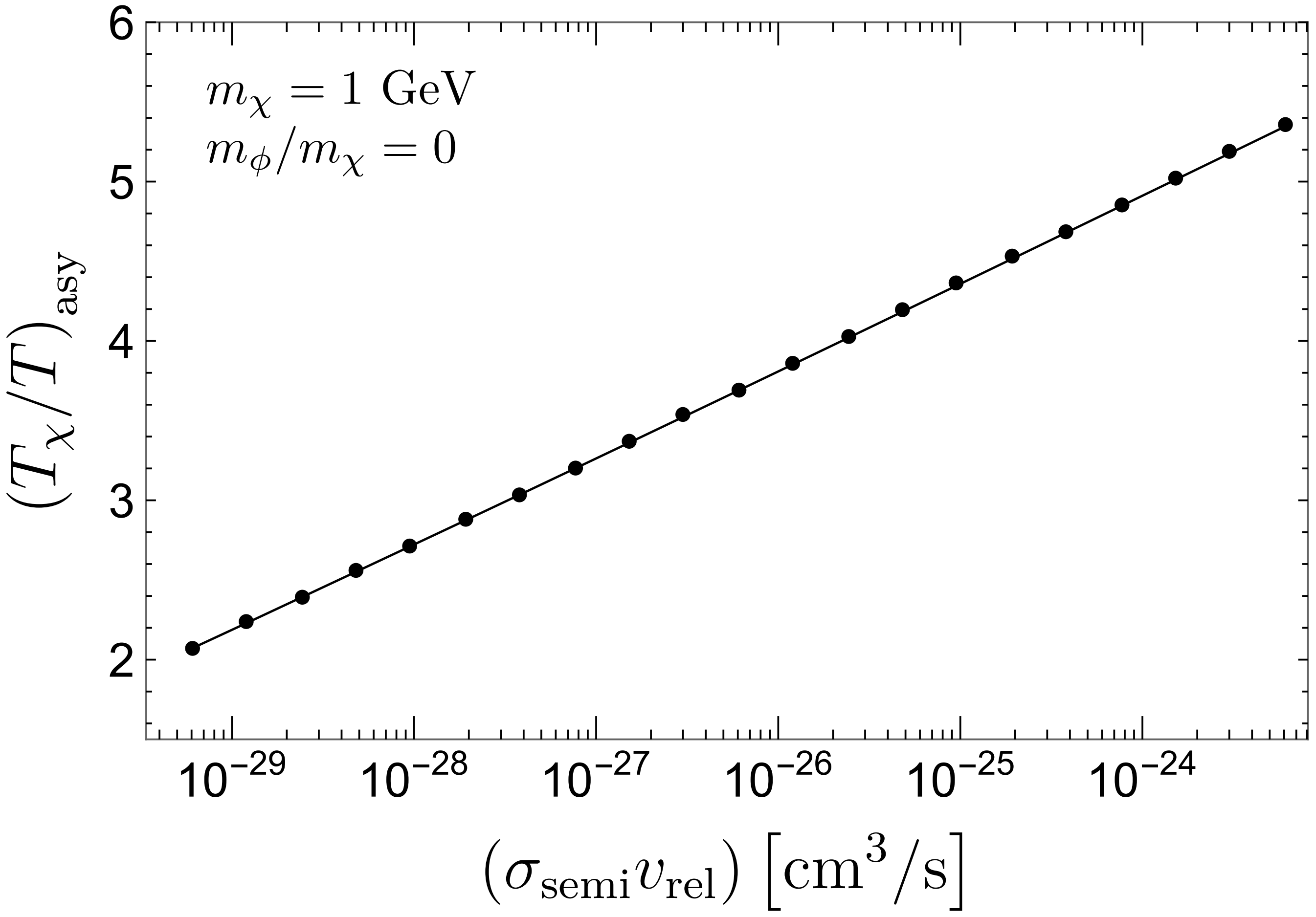
heating through the semi-annihilation

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

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



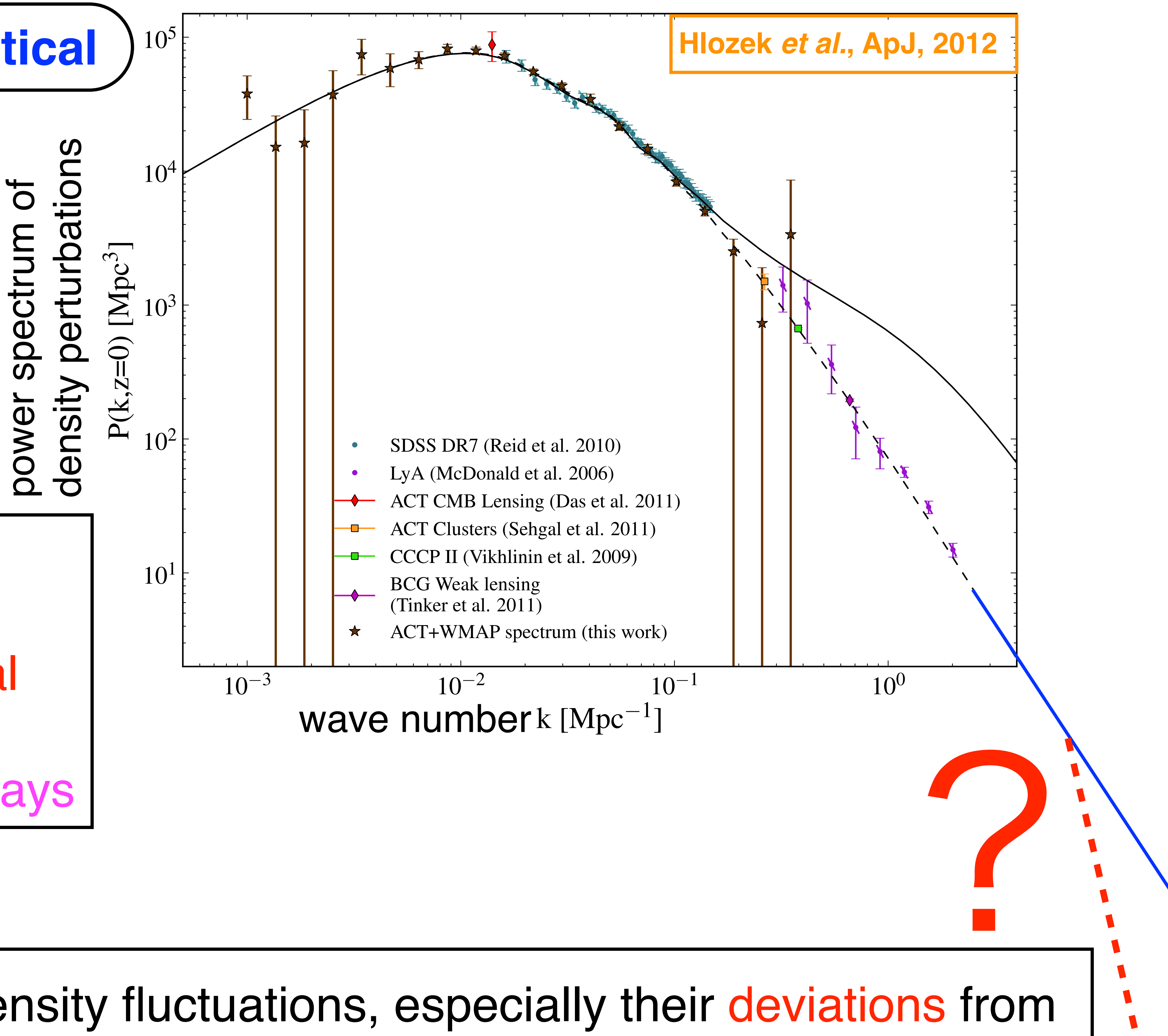
Cold Dark Matter?

hypothetical

cold dark matter:
null thermal velocity
only gravitationally interacting

↕

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



Hlozek *et al.*, ApJ, 2012

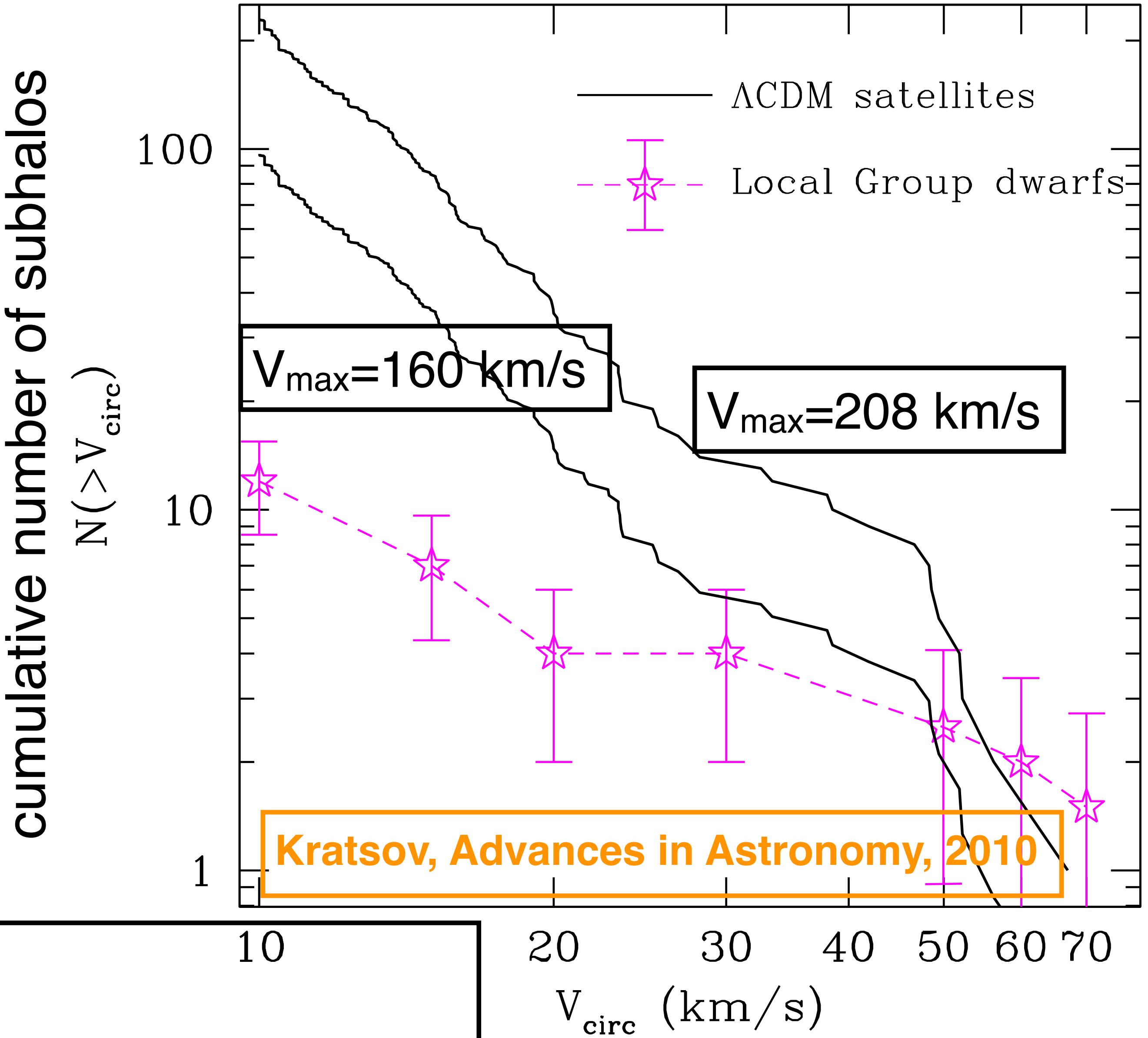
Small scale matter density fluctuations, especially their deviations from the ΛCDM model, contain imprints of the nature of DM

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



Kratsov, Advances in Astronomy, 2010

maximal circular velocity of subhalo

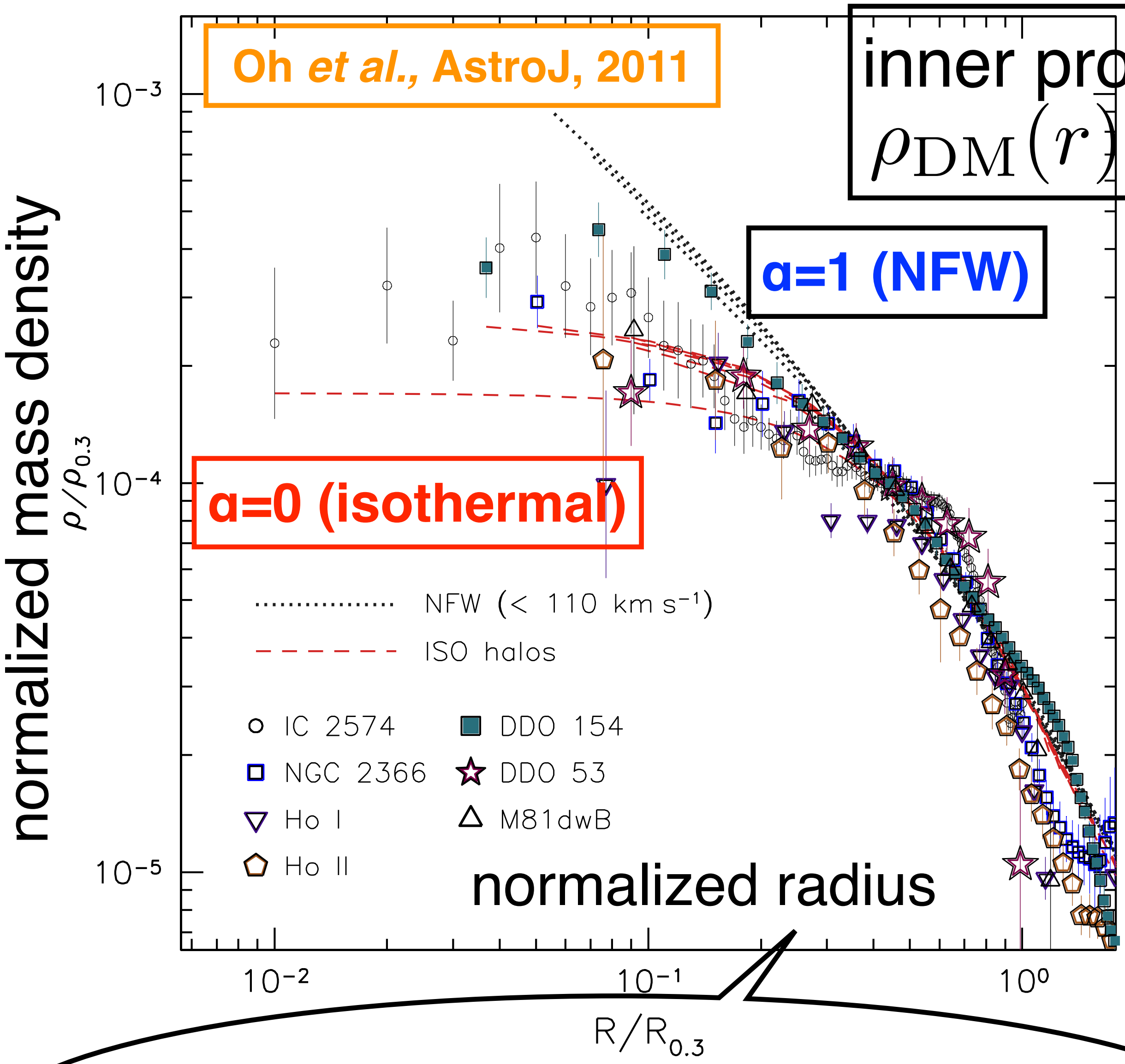
(maximum) circular velocity

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

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**



normalized mass density

Oh *et al.*, AstroJ, 2011

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

α=1 (NFW)

α=0 (isothermal)

normalized radius

field dwarf spheroidal galaxies
~10⁹ 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:

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

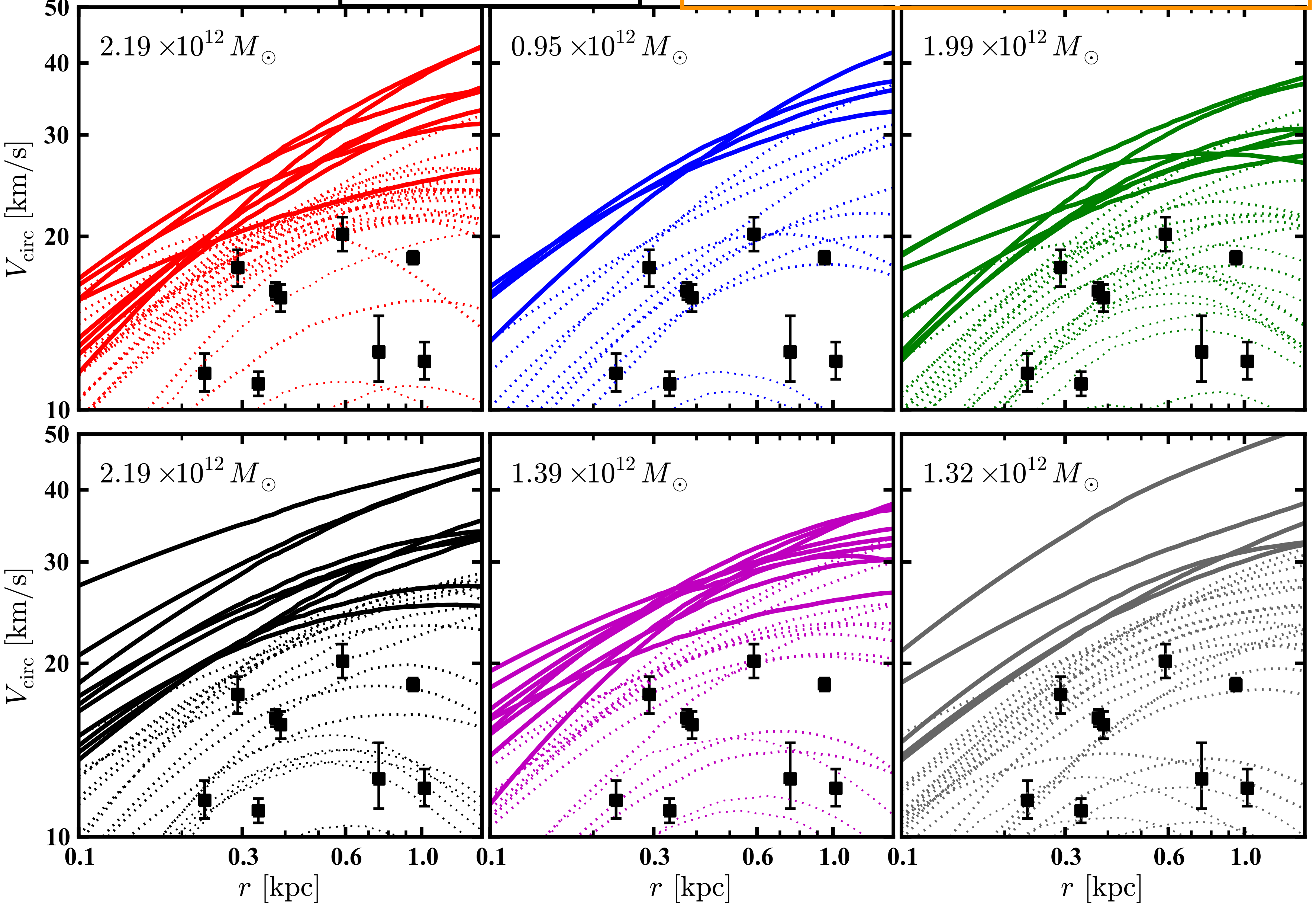
Small scale crisis III

too big to fail problem

MW-like halos

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

circular velocity of subhalos



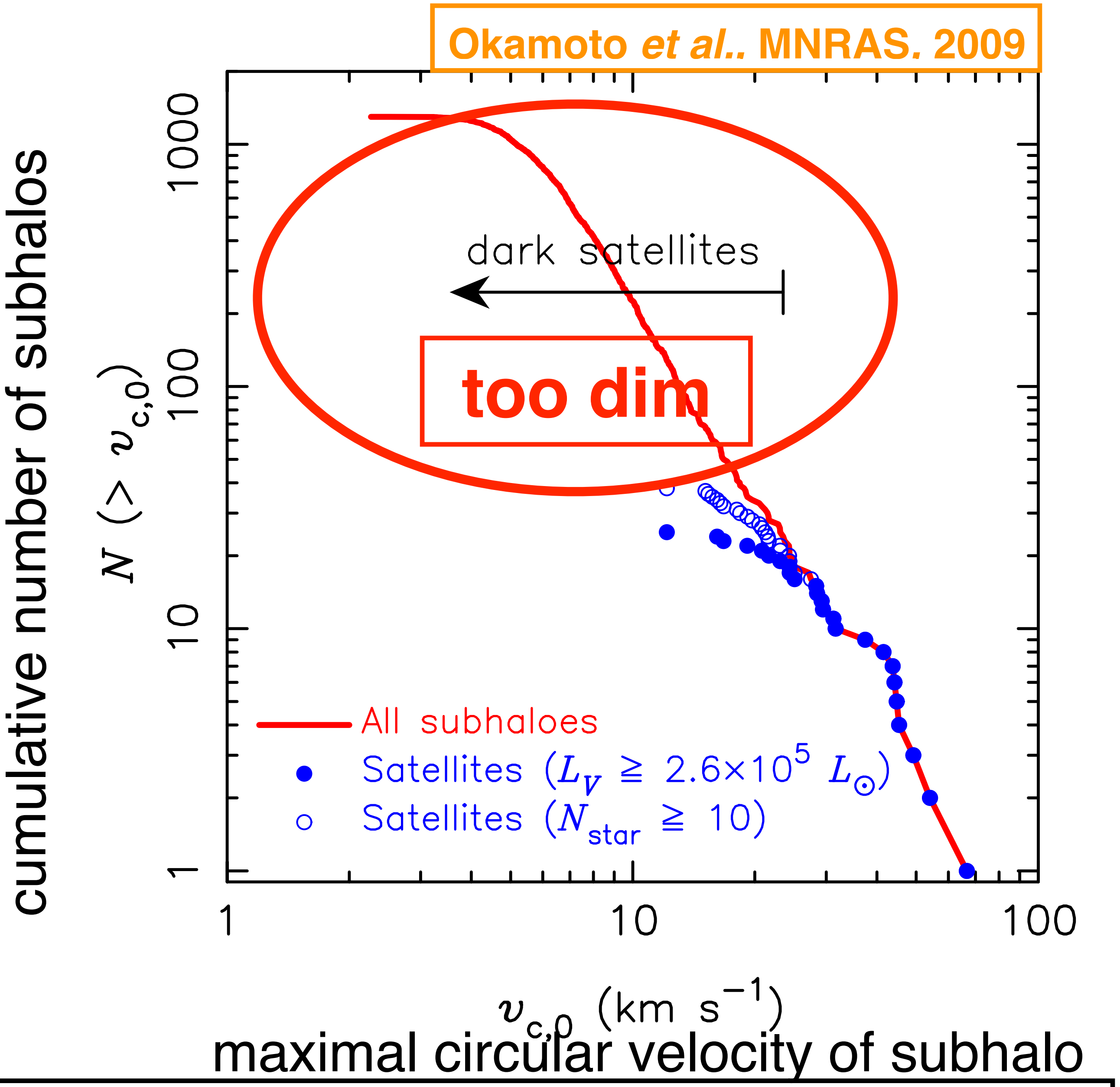
radius

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


Okamoto *et al.*. MNRAS. 2009

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

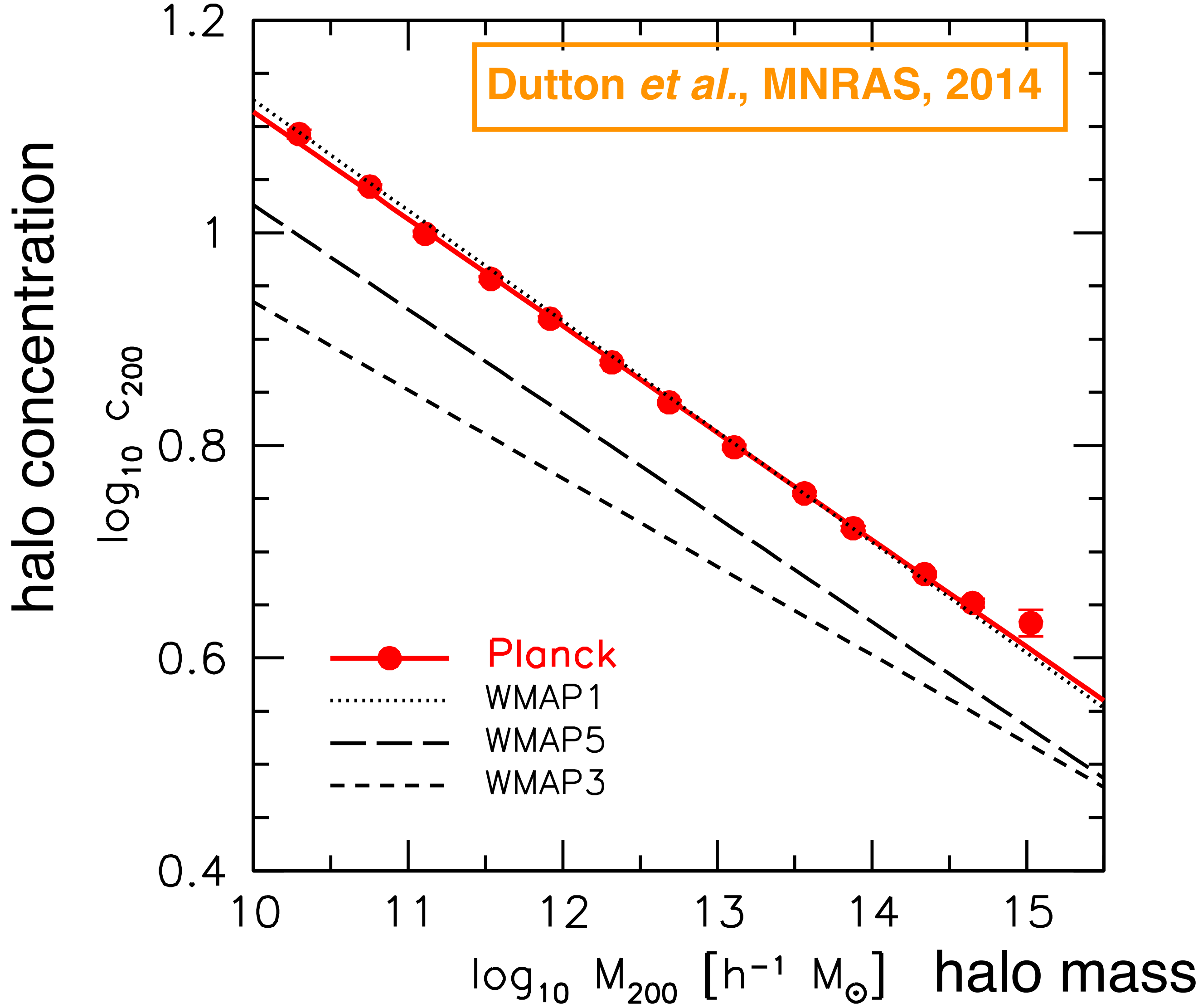
Why is a simulated rotation curve (almost) **DEFINITE** for a given $V_{\max}$?

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**

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



Dutton *et al.*, MNRAS, 2014

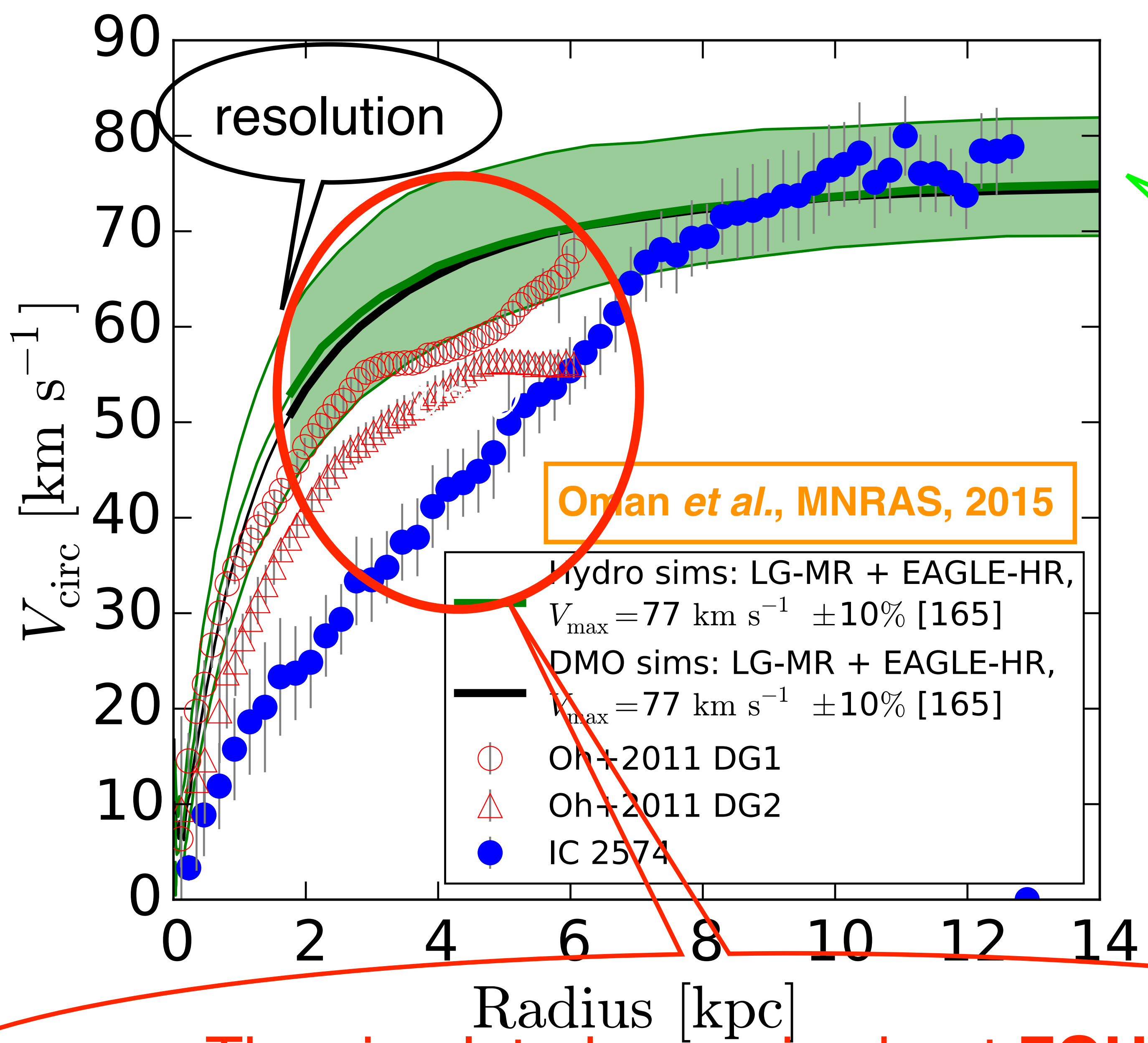
small intrinsic scatter

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

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

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.



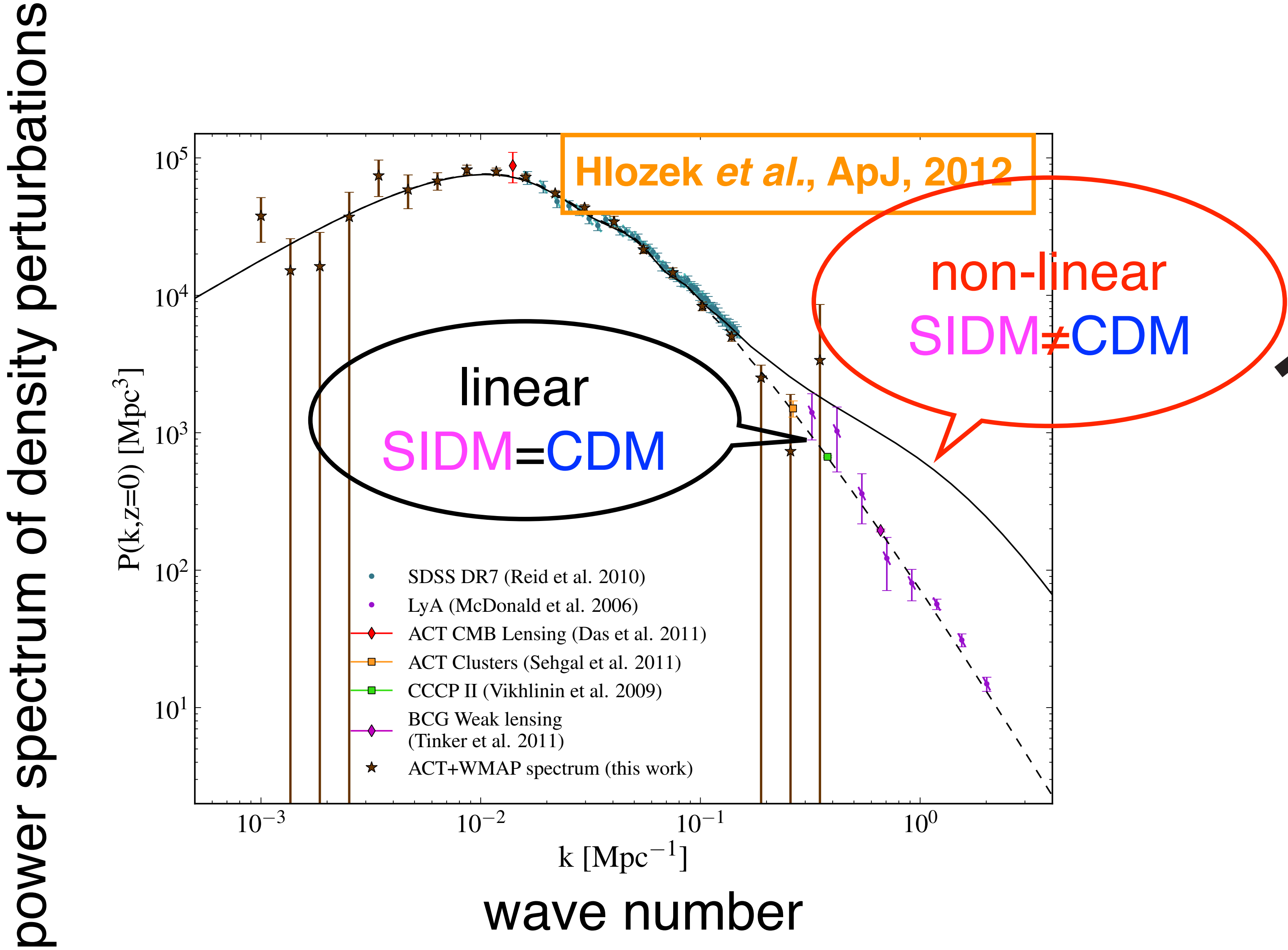
Oman *et al.*, MNRAS, 2015

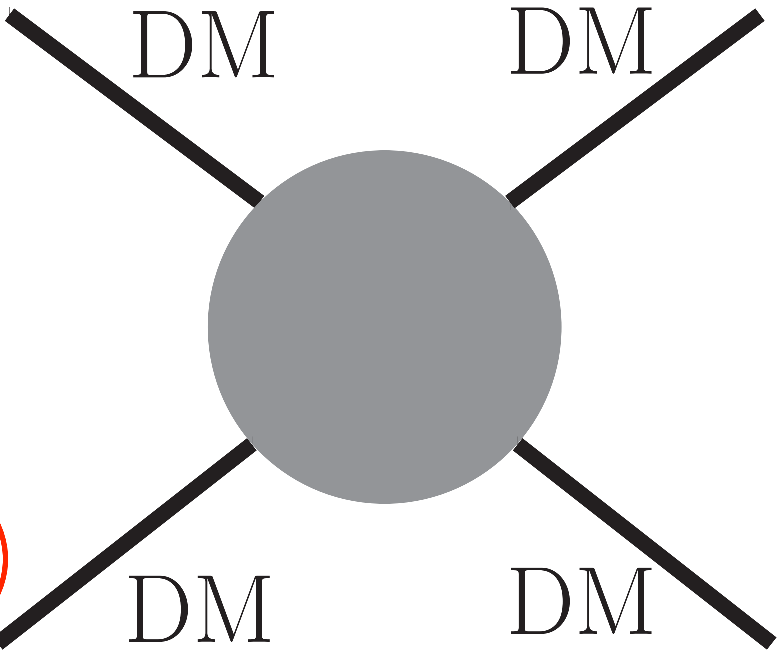
10th-90th percentile range from the state-of-the-art hydrodynamical simulations in the ΛCDM model (*EAGLE, Local GROUPS*) with modeled subgrid baryonic physics (radiative cooling, star formation, stellar and chemical enrichment, energetic stellar feedback, black hole accretion and mergers, and AGN feedback)

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

Dark matter self-interaction

Self-Interacting Dark Matter: **SIDM**





Reaction rate Γ=σvρ/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

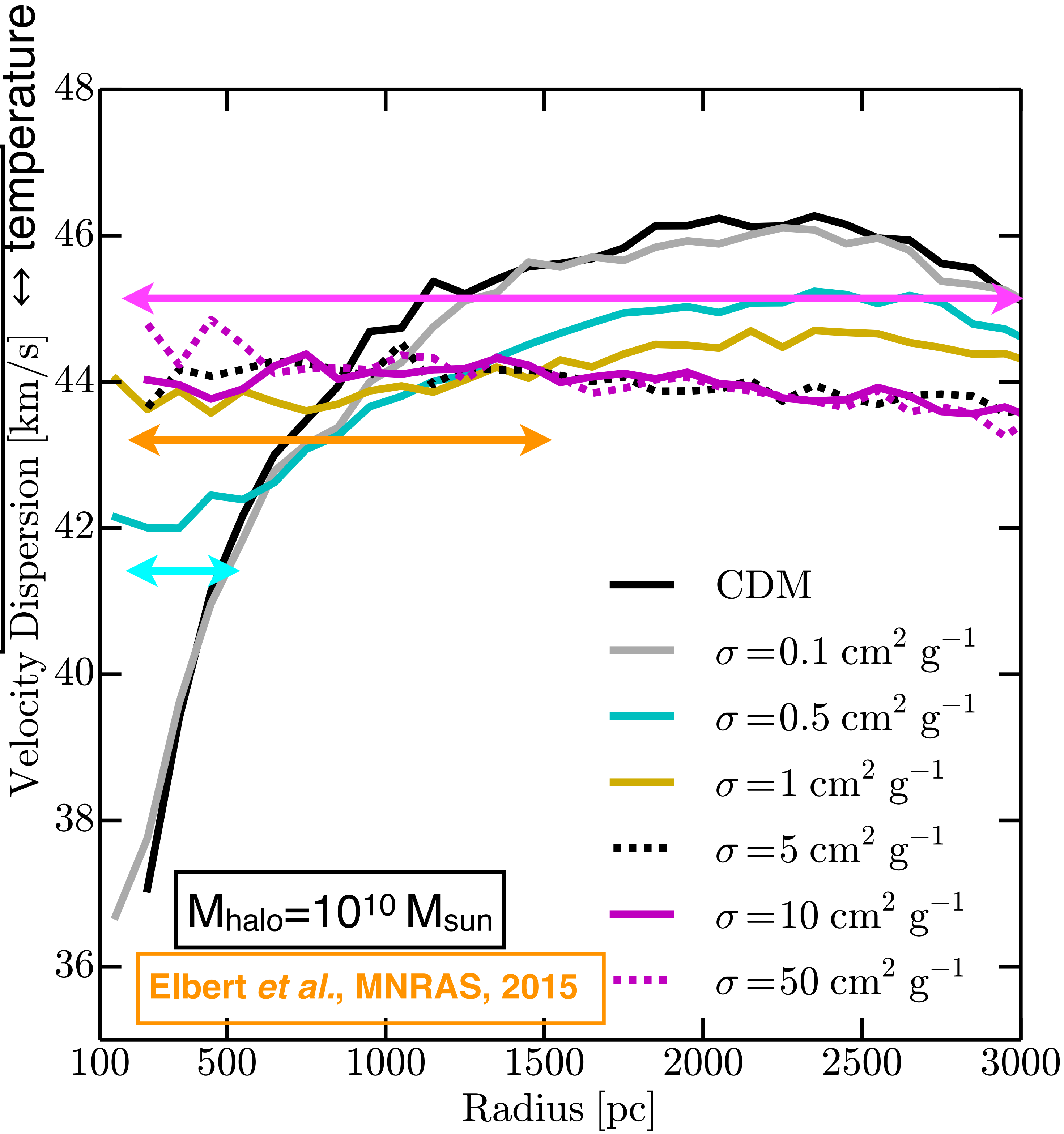
SIDM-only simulation

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

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



$M_{halo}=10^{10}\ M_{sun}$

Elbert *et al.*, MNRAS, 2015

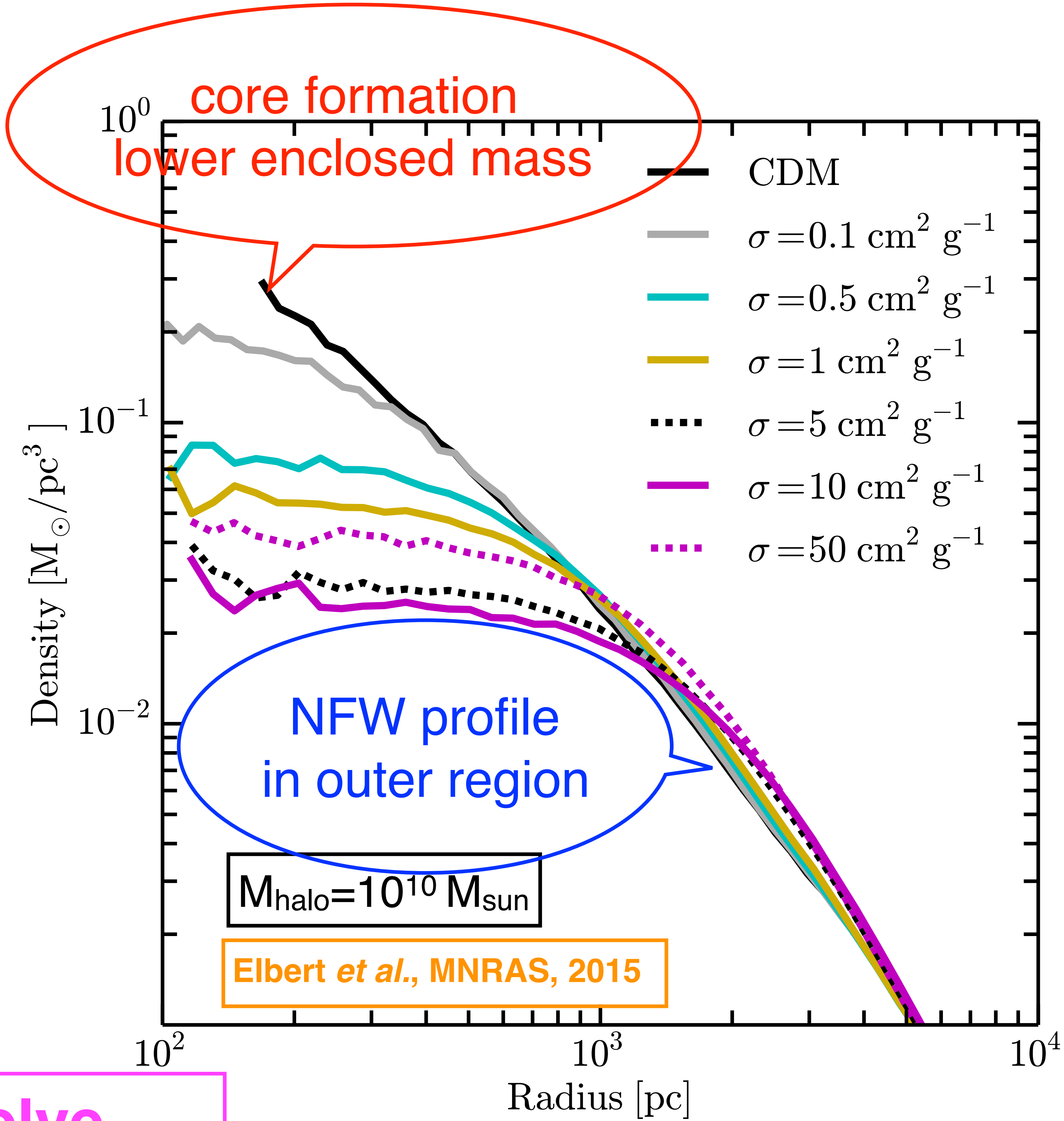
SIDM halo - mass density

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**



core formation
lower enclosed mass

NFW profile
in outer region

$M_{halo}=10^{10}\ M_{sun}$

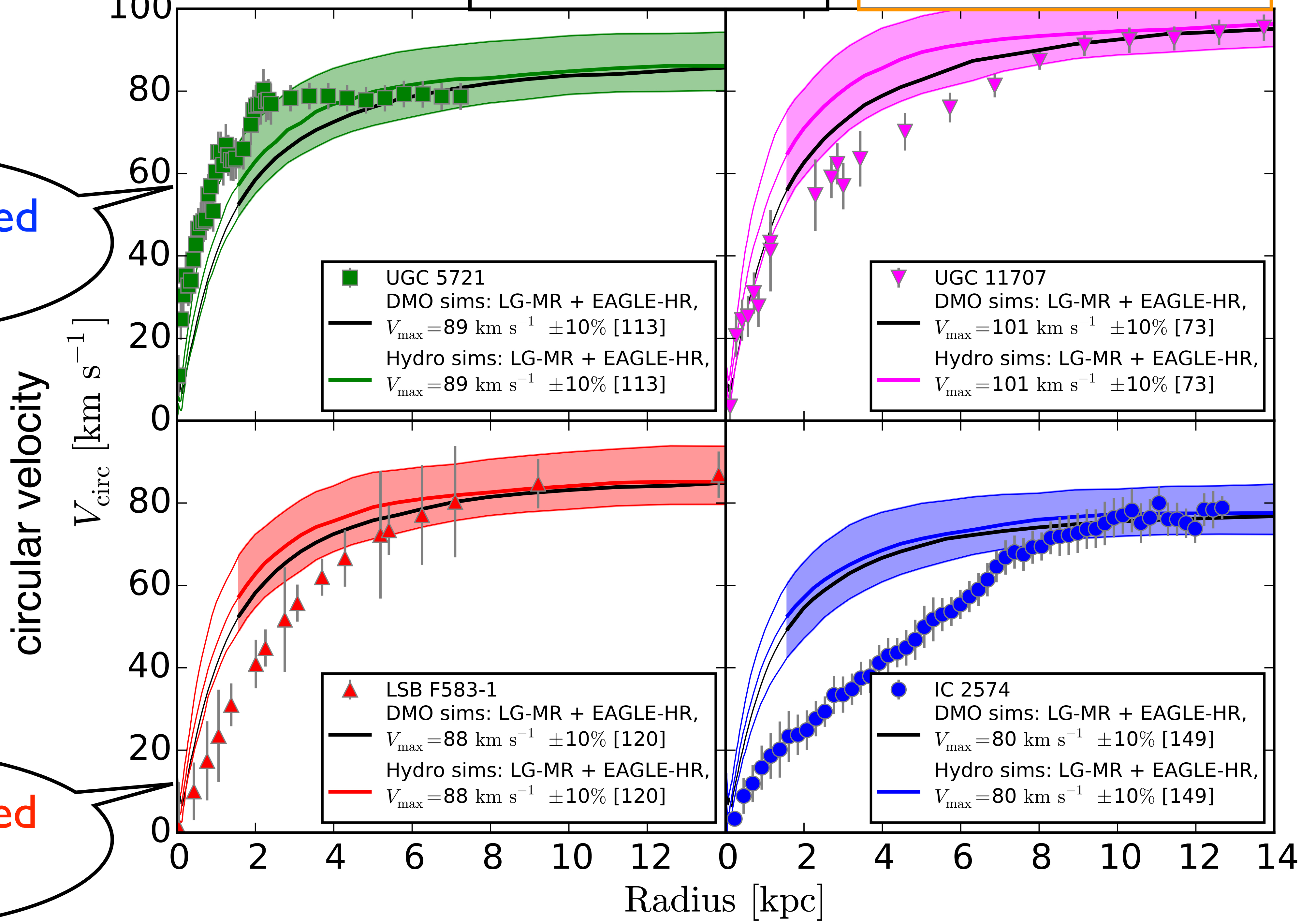
Elbert *et al.*, MNRAS, 2015

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**.

V_{max}=80-100 km/s

Oman *et al.*, MNRAS, 2015



well-reproduced

badly-reproduced

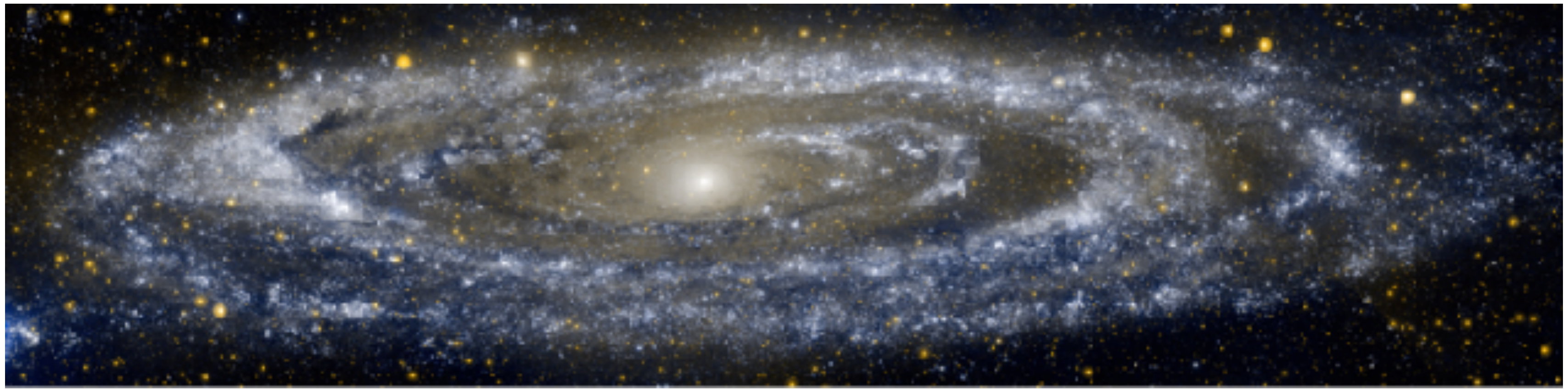
Origin of the diversity

Unexpected diversity problem??

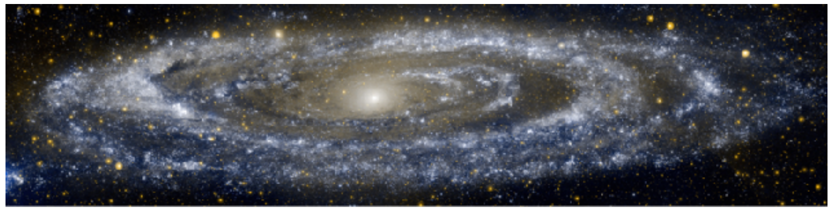
⇔ For a given cross section ($\sigma/m=3\ \mathrm{cm^2/g}$ in the following), SIDM halo profile is still **DEFINITE** and characterized by only one parameter V_{max}

Scatter in distributions of the baryons even 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:

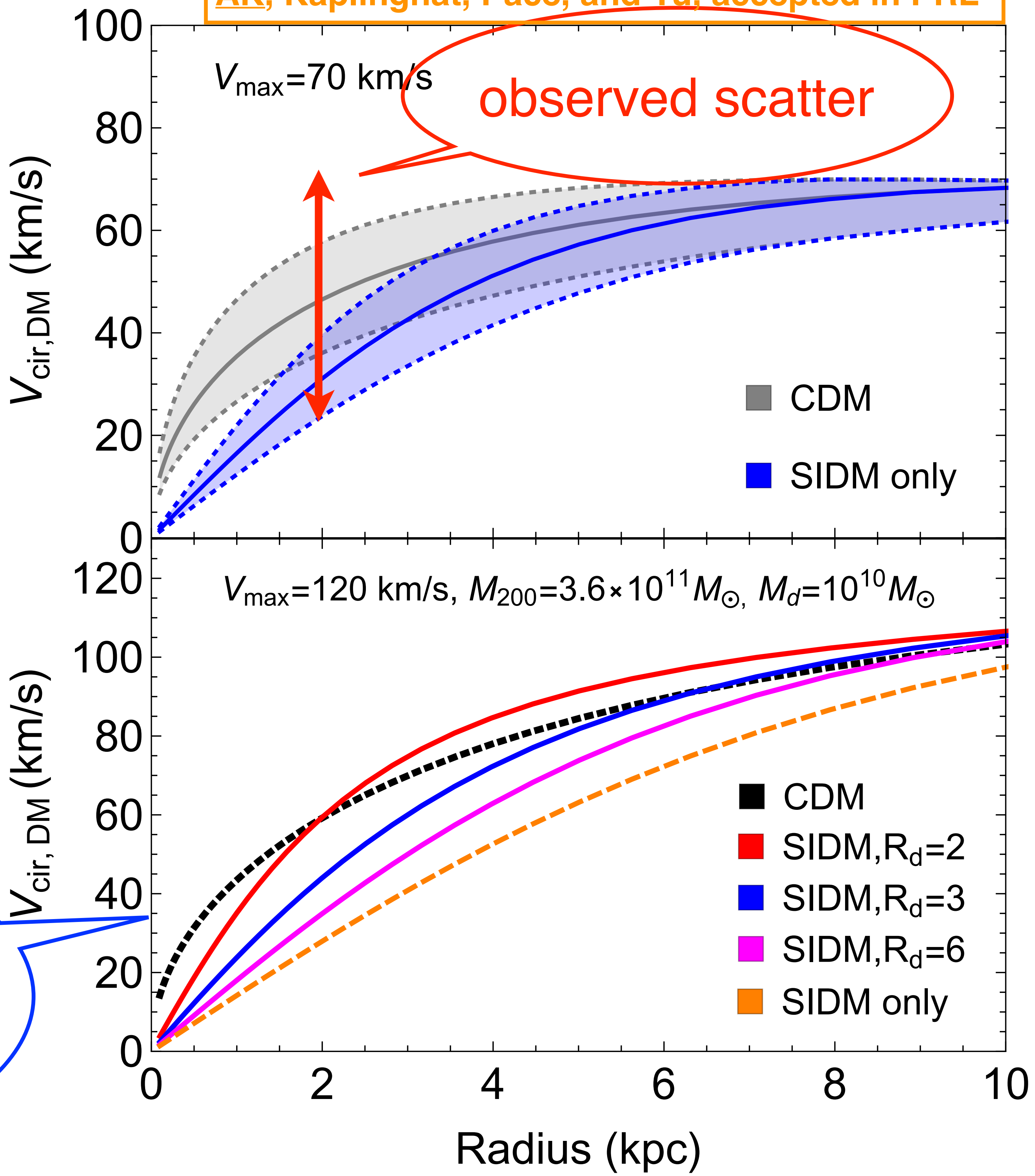
$$\Delta\phi = 4\pi G\rho_{\rm DM}^{0}\exp(-\phi/\sigma^2)$$

$$\phi(0) = 0$$

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

$$V_\infty^2 = 2\sigma^2 = 4\pi G\rho_{\rm DM}^{0} r_0^2$$

AK, Kaplinghat, Pace, and Yu, accepted in PRL

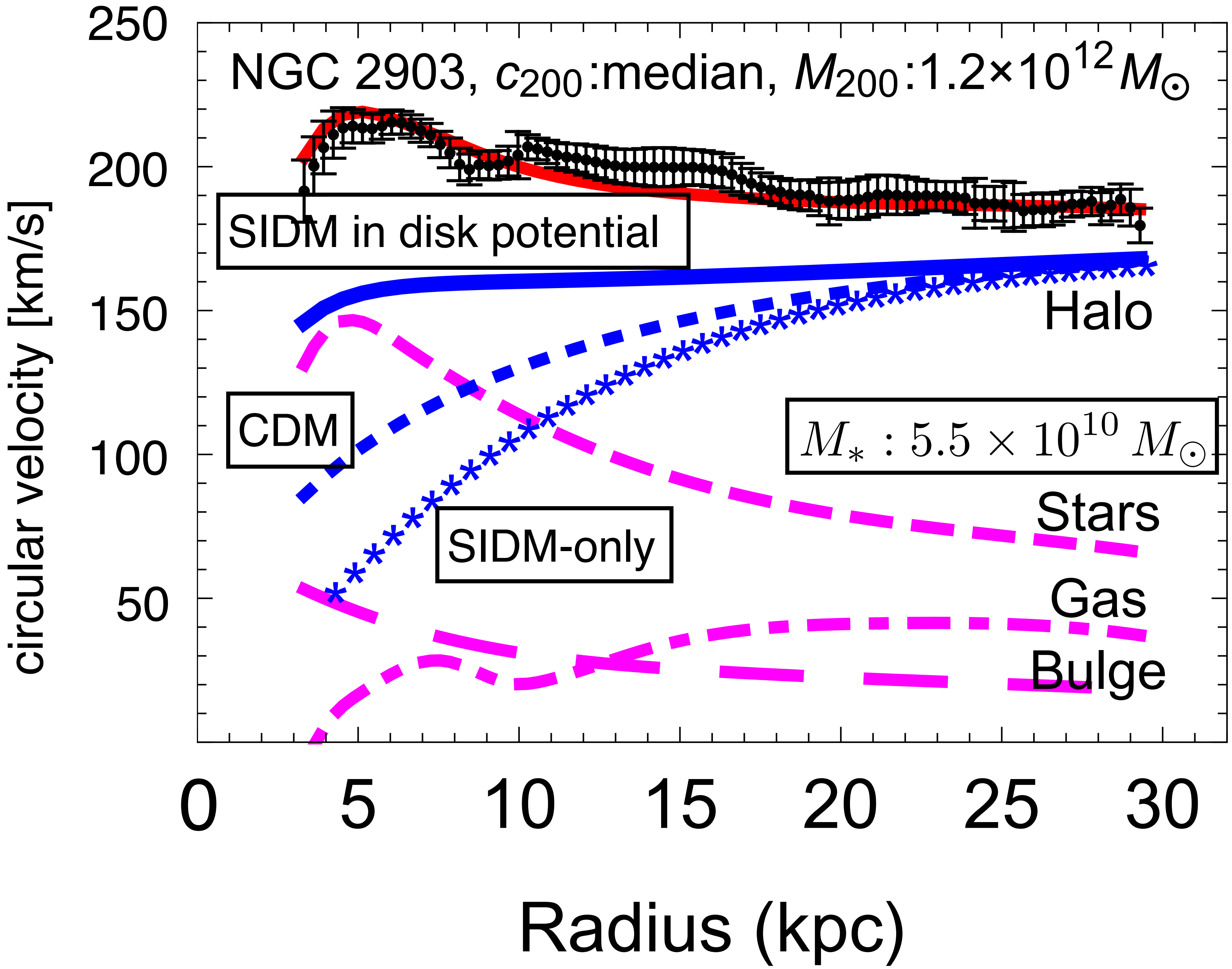


observed scatter

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

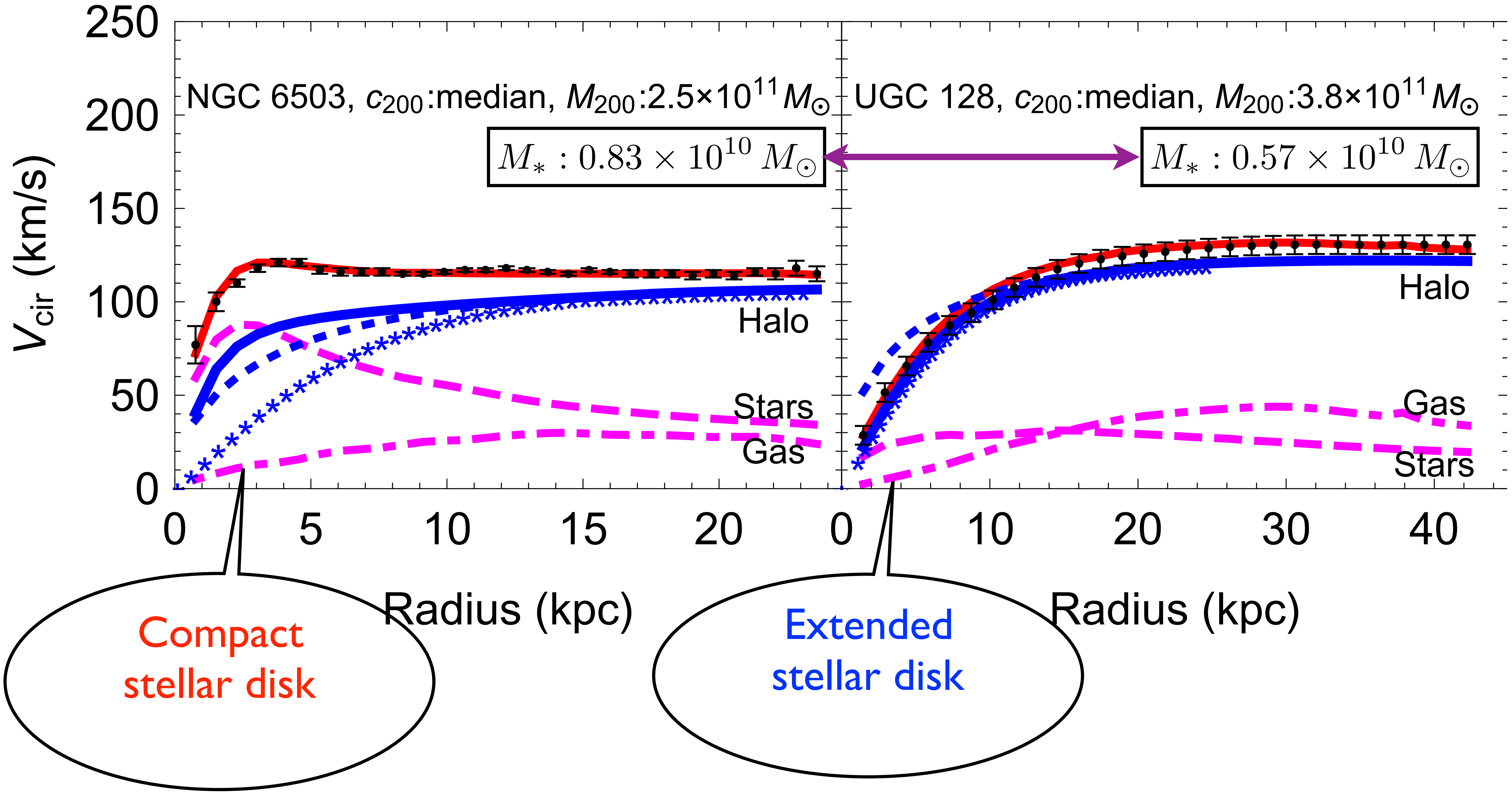
Case study I

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_***

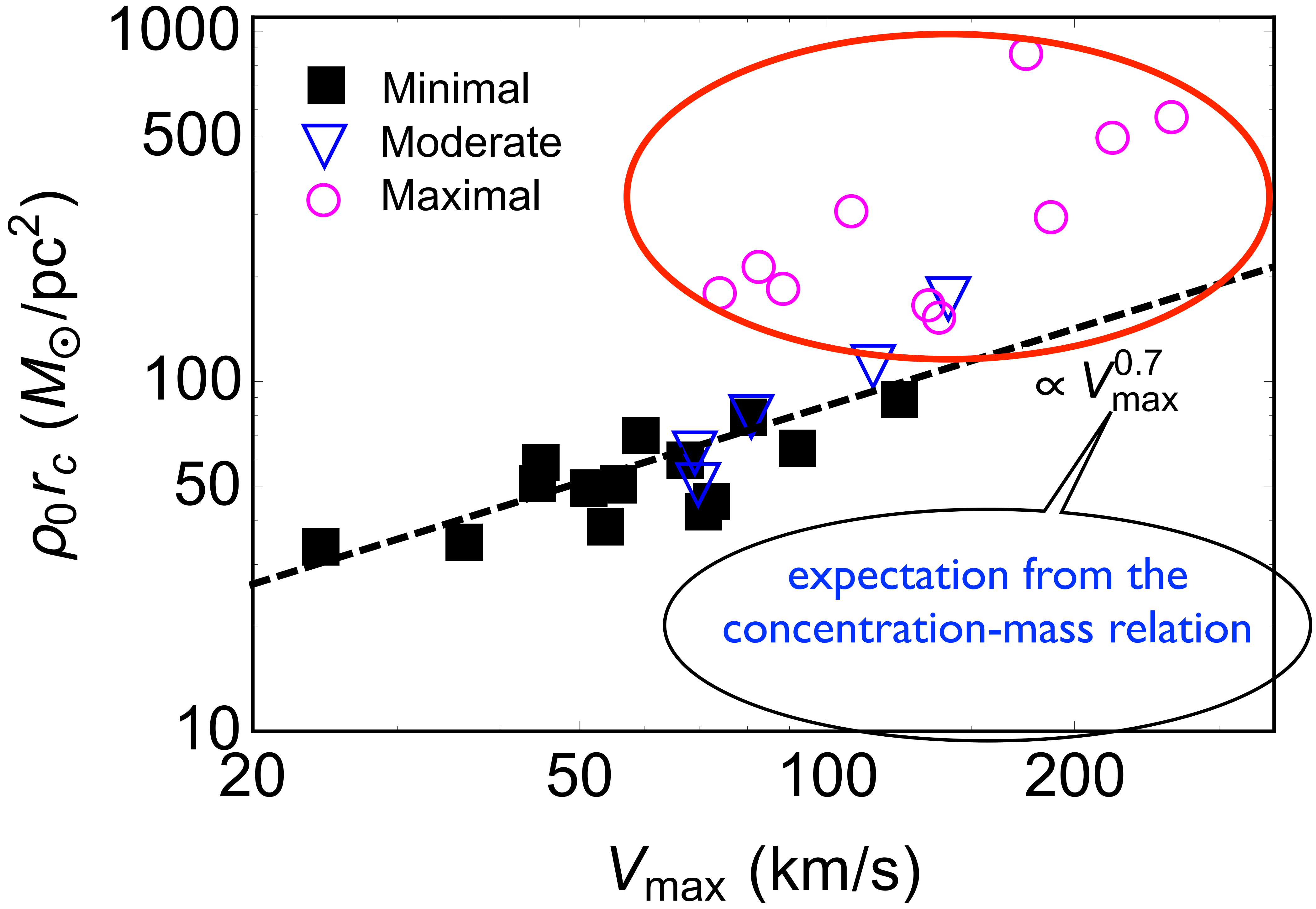


Compact stellar disk

Extended stellar disk

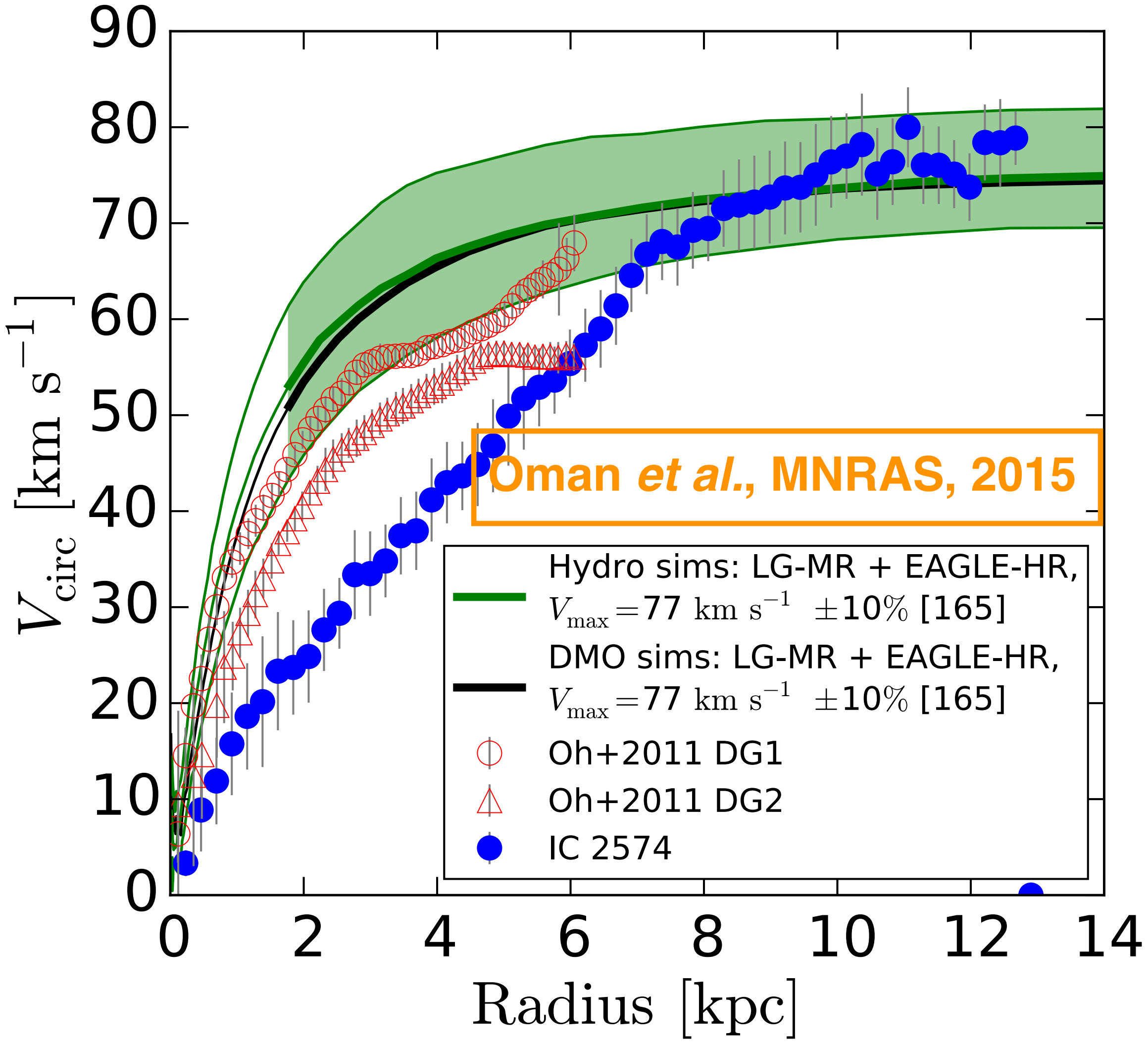
More samples

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

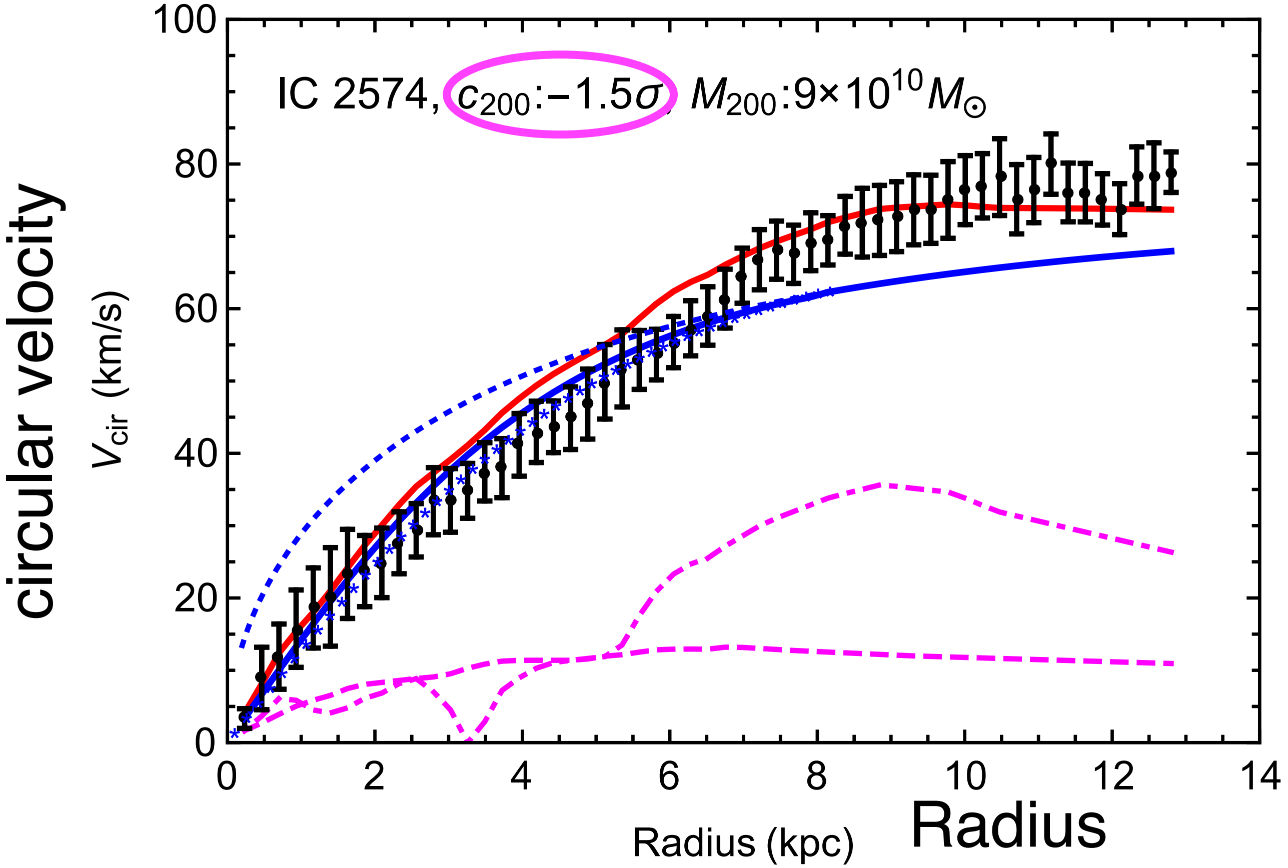


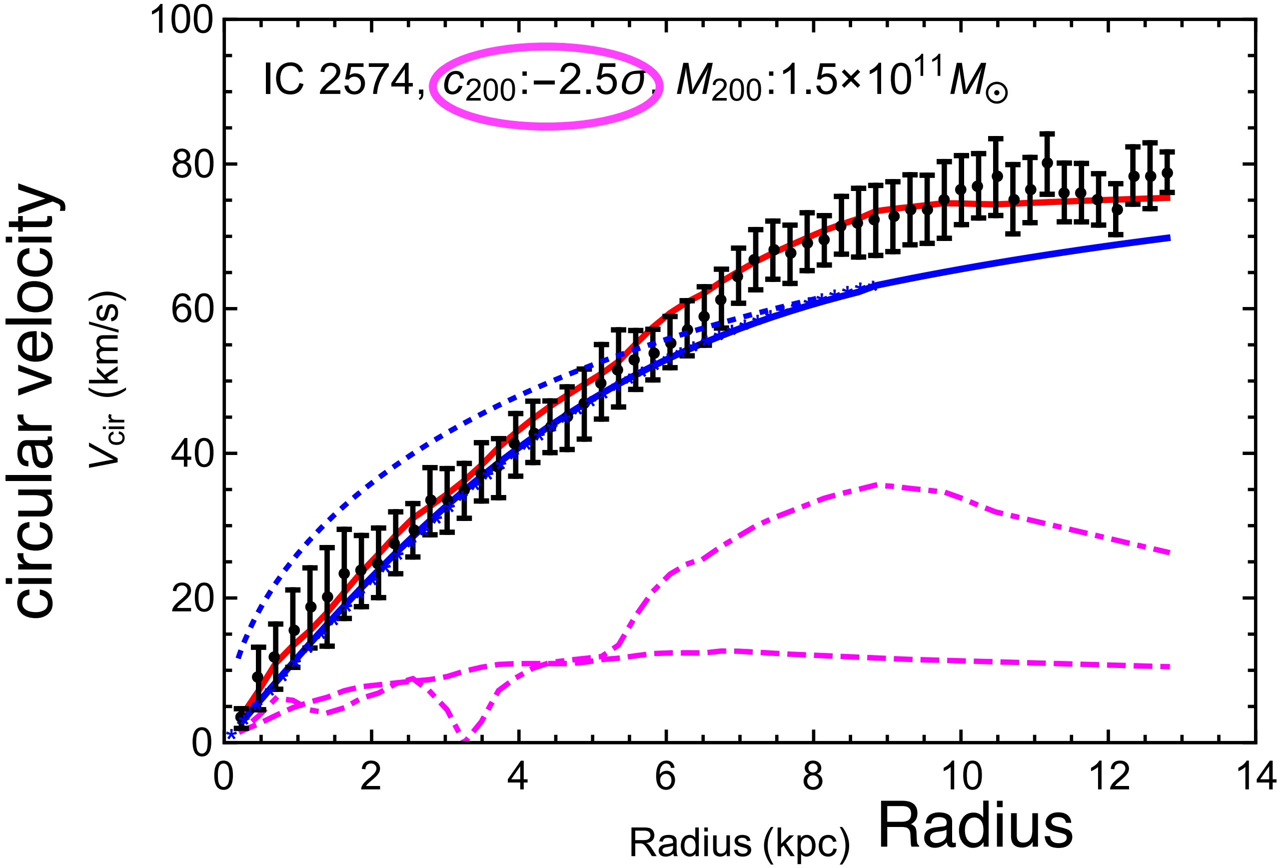
Case study III

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

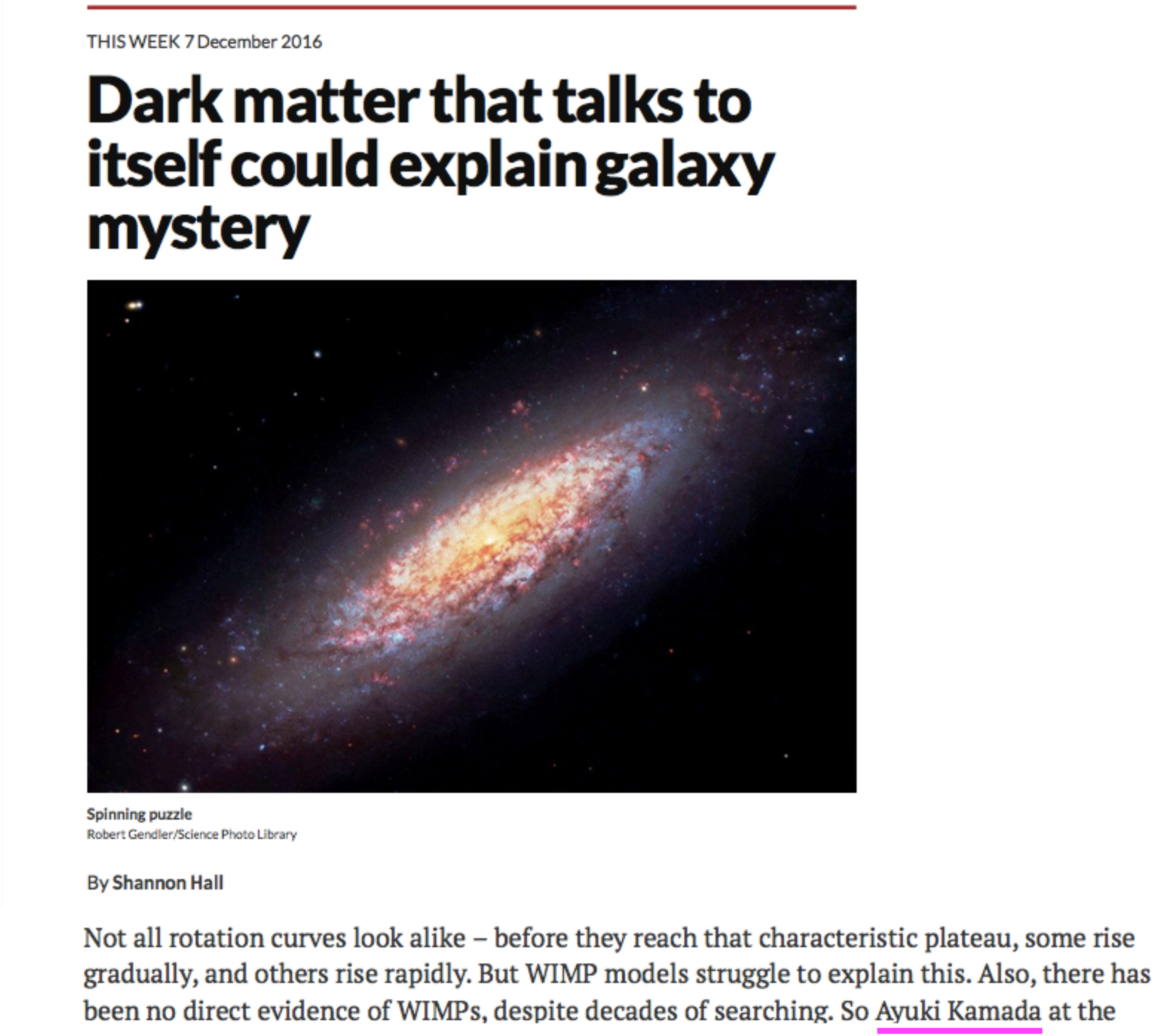


Oman *et al.*, MNRAS, 2015





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

Constraints from galaxy clusters

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

$\sigma/m=0.5\text{-}10\ cm^2/g$

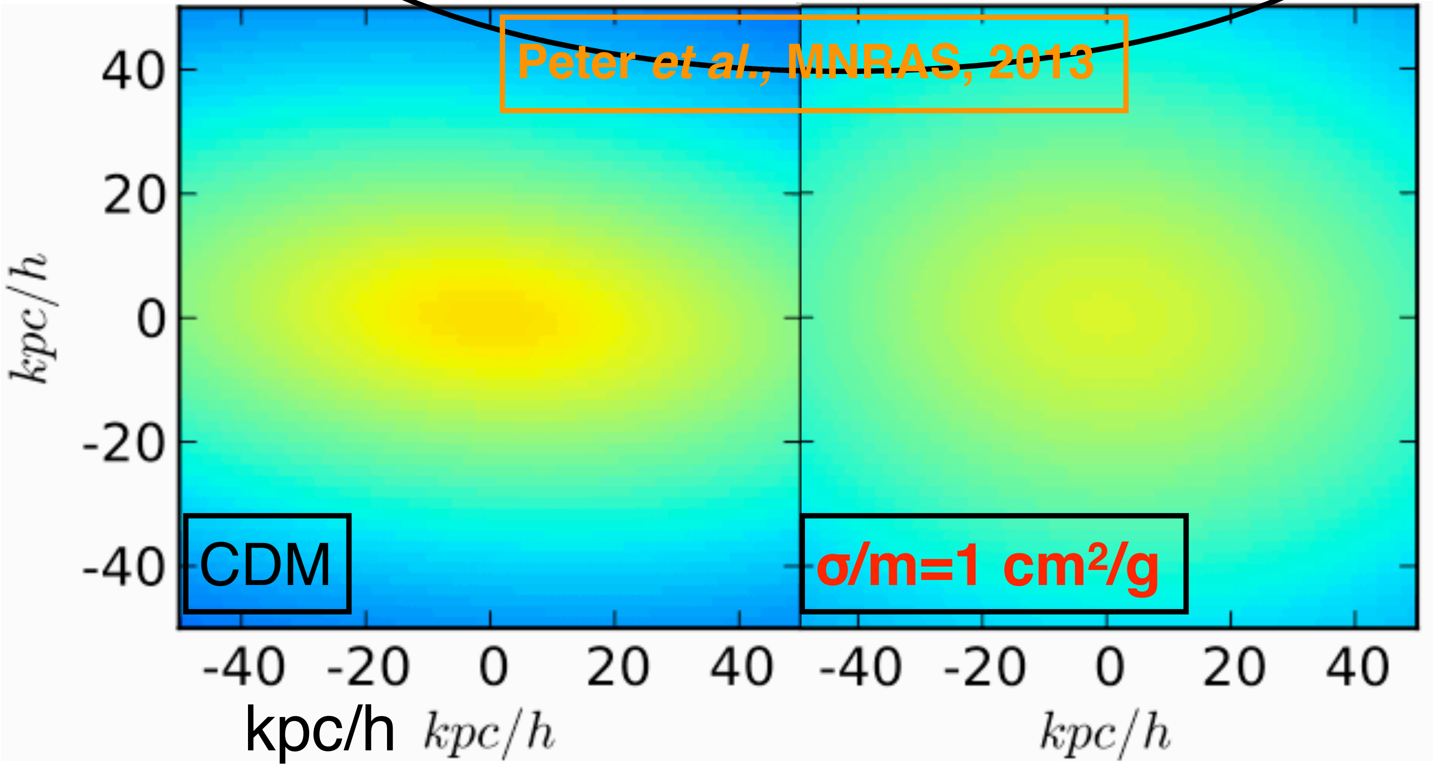
Halo shape - ellipticity
- galaxy cluster MS 2137–23
  (e=0.18@r=70 kpc)

(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



Peter *et al.*, MNRAS, 2013

Bullet cluster - transparency
- 1E0657-558

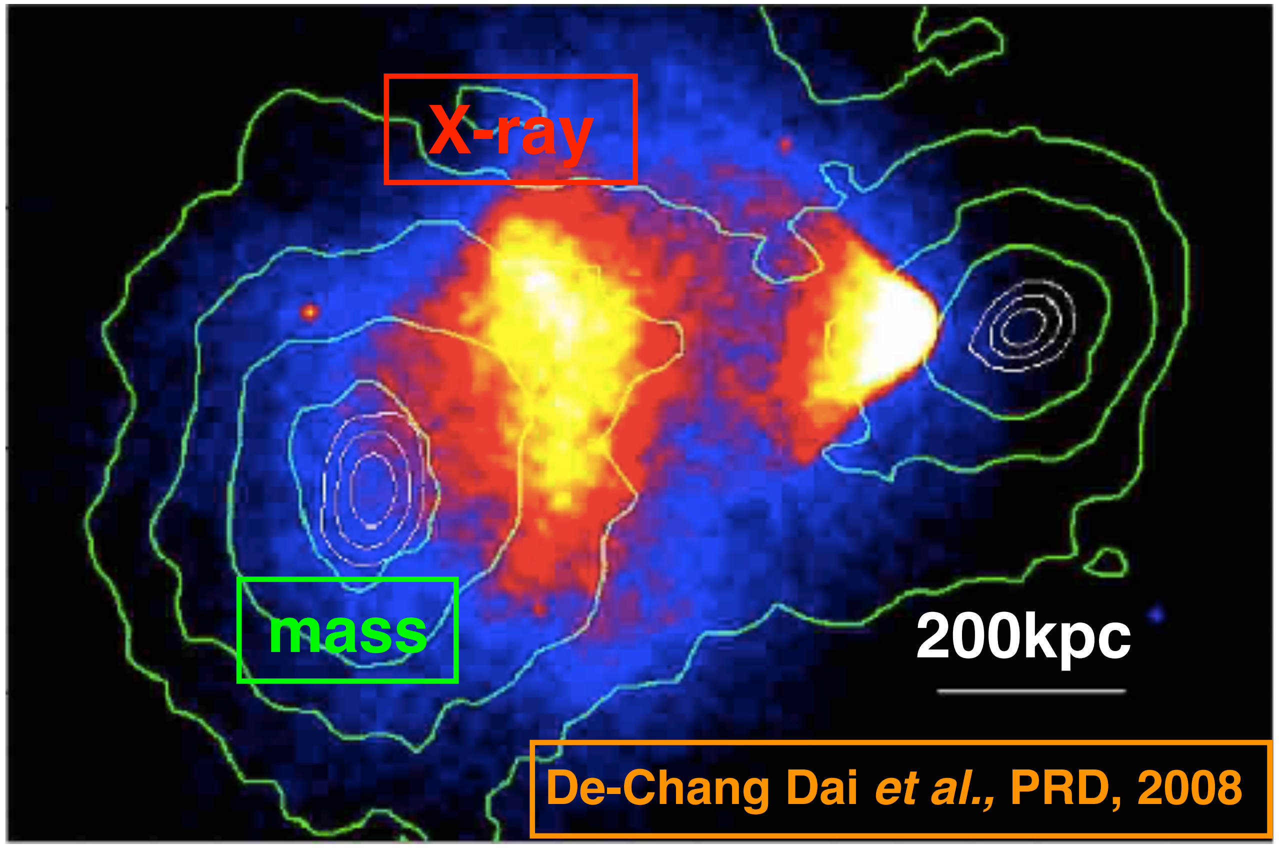
(offset) $\sigma/m<1.25\ cm^2/g$
(massloss) $\sigma/m<0.7\ cm^2/g$

Randall *et al.*, ApJ, 2008

- an ensemble (72)

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

Harvey *et al.*, Science, 2015



De-Chang Dai *et al.*, PRD, 2008

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 **$\sigma/m=0.1\ \mathrm{cm}^2/\mathrm{g}$**

Tulin *et al.*, PRL, 2012

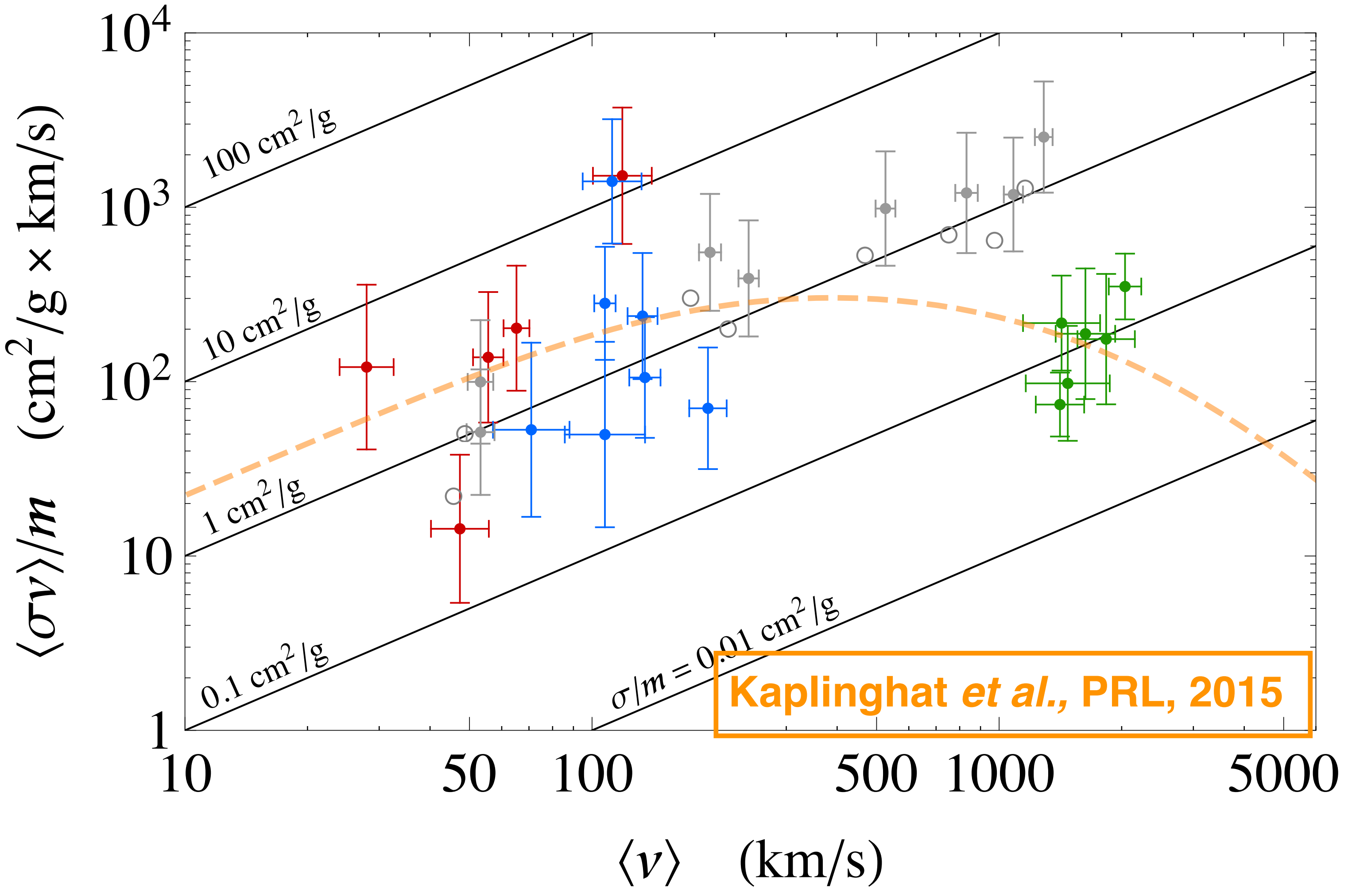
velocity-DEPENDENT cross section:

WIMP dark matter
+ light mediator with

$m_{med} \sim m_{DM}\, v_{gal}/c$

$\sigma \sim 1/m_{med}^2$: const.
@ (dwarf) galaxies
($V_{max} \sim$10-100 km/s)

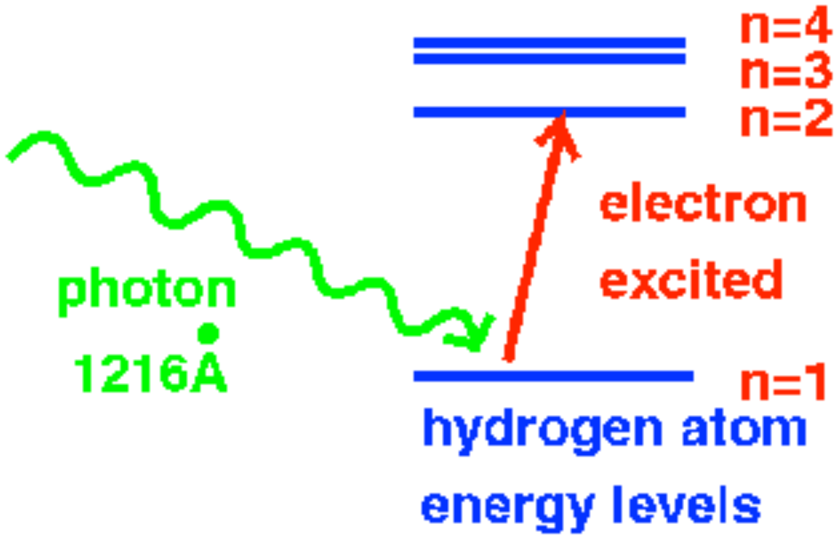
$\sigma \sim 1/v^4$: suppressed
@ galaxy cluster
($V_{max} \sim$1000 km/s)

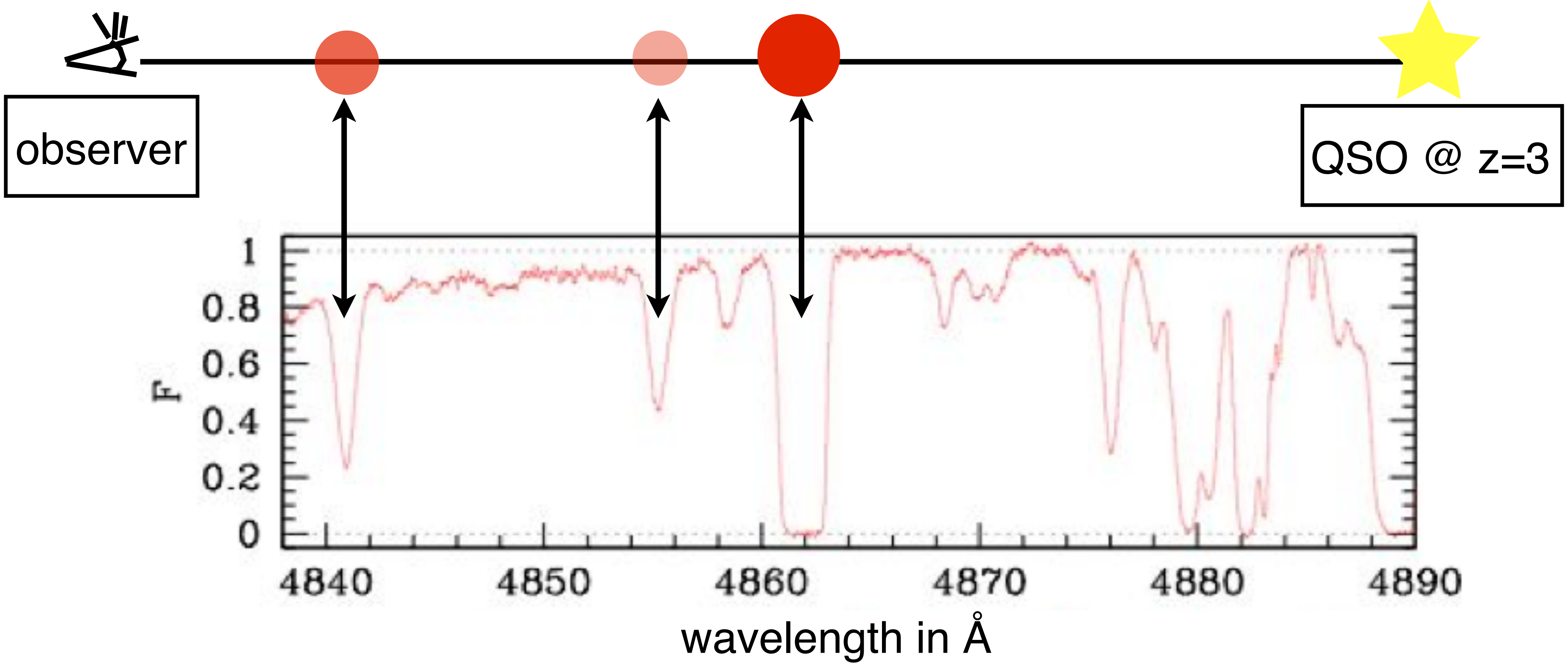


Kaplinghat *et al.*, PRL, 2015

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

Mass fraction of the hot component

Decoupling of self-scattering:

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

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

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