# Self-heating dark matter in the early Universe

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Ayuki Kamada, Hee Jung Kim, Hyungjin Kim, Toyokazu Sekiguchi, PRL (2018)

A. Kamada, Hee Jung Kim, Hyungjin Kim, PRD (2018)

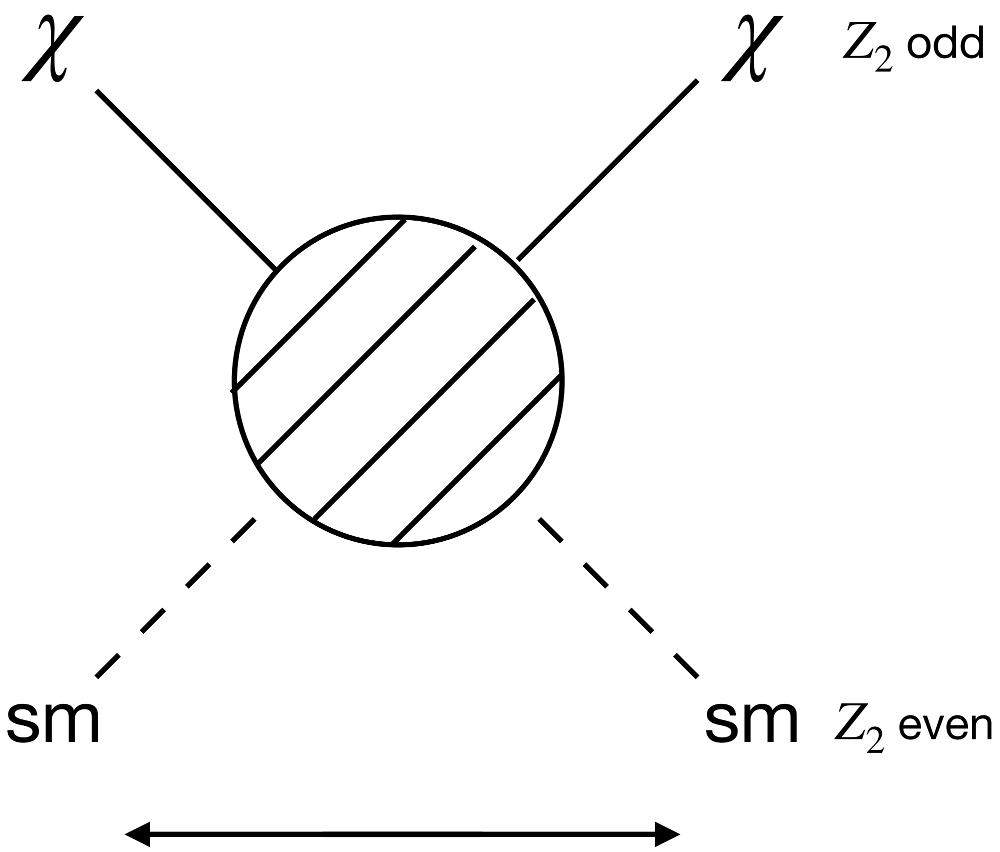
DM is stable over the age of the Universe, $\tau \gtrsim 10^{18}\,\mathrm{s}$.

(if DM decays into SM states, $\tau \gtrsim 10^{26}\,\mathrm{s}$)

Symmetry (fundamental or accidental) guarantees their longevity.

*It influences the structure of the model and therefore the phenomenology.*

# $Z_2$ symmetry



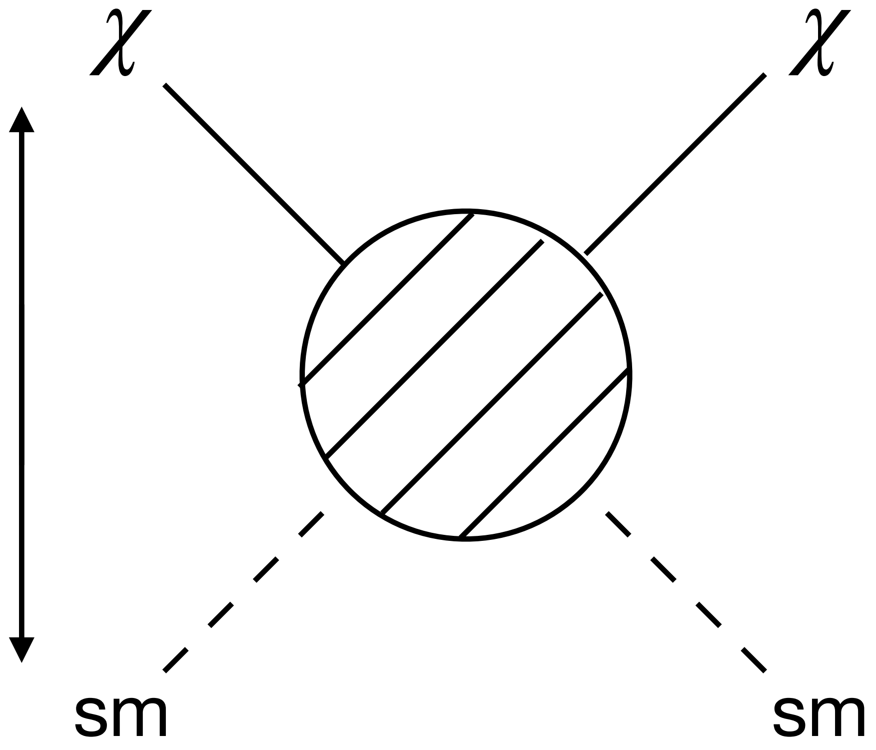
*Efficient elastic scattering equilibrate temperature of SM and DM.*

$T_\chi = T$ *until* $T/m_\chi \times n_{\rm sm} \langle \sigma v \rangle_{\rm el} \simeq H$ .

T. Bringmann et. al., JCAP (2008)

T. Binder et. al., JHEP (2018)

# $Z_2$ symmetry

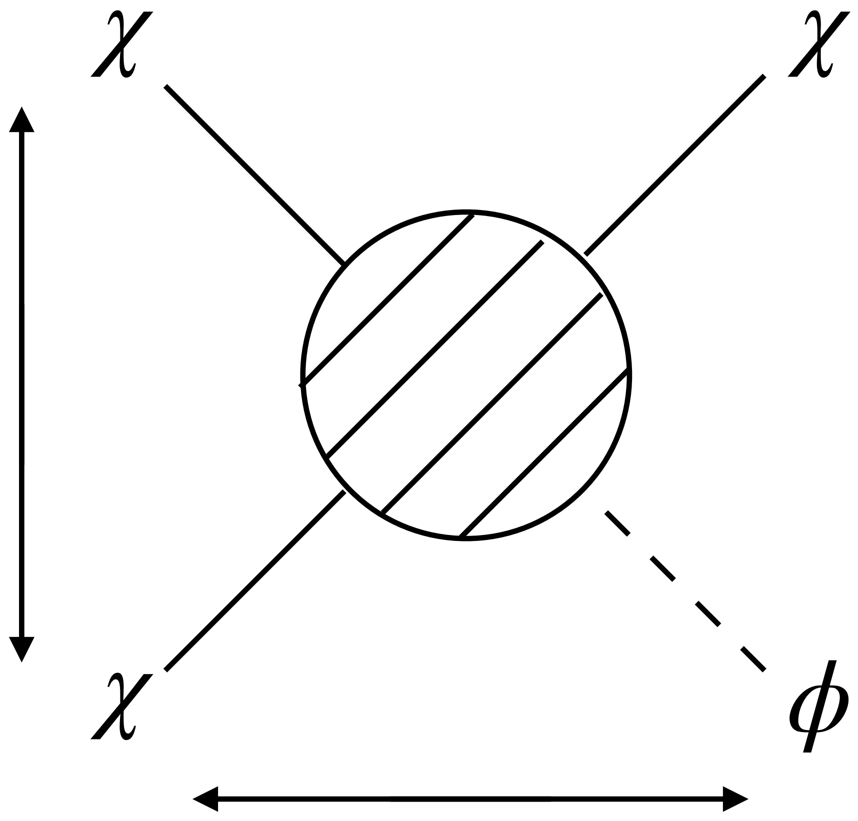


*Pair annihilation/creation changes DM number and redistribute DM energy.*

*DM number density freezes when* $n_\chi \langle \sigma v \rangle_{\mathrm{ann}} \simeq H$ *.*

(observed relic abundance when $m_\chi = \mathcal{O}(100)\,\mathrm{GeV}$, $\langle \sigma v \rangle_{\mathrm{ann}} \simeq 10^{-\mathrm{few}} \times 1\,\mathrm{pb}$)

# semi-annihilation



It is realized when DM is stabilized by a larger symmetry.

T. Hambye, JHEP (2009)

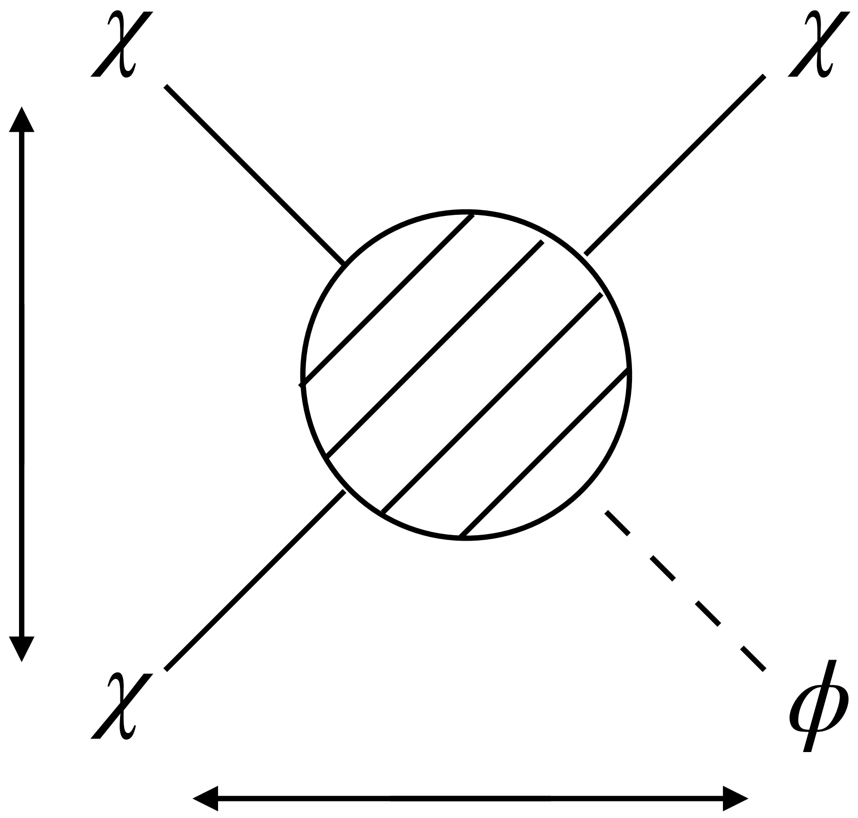
F. D'Eramo, J. Thaler, JHEP (2010)

A. Kamada et. al., PRD (2017)

*When do two sectors kinetically decouple?*

*What happens to the freeze-out?*

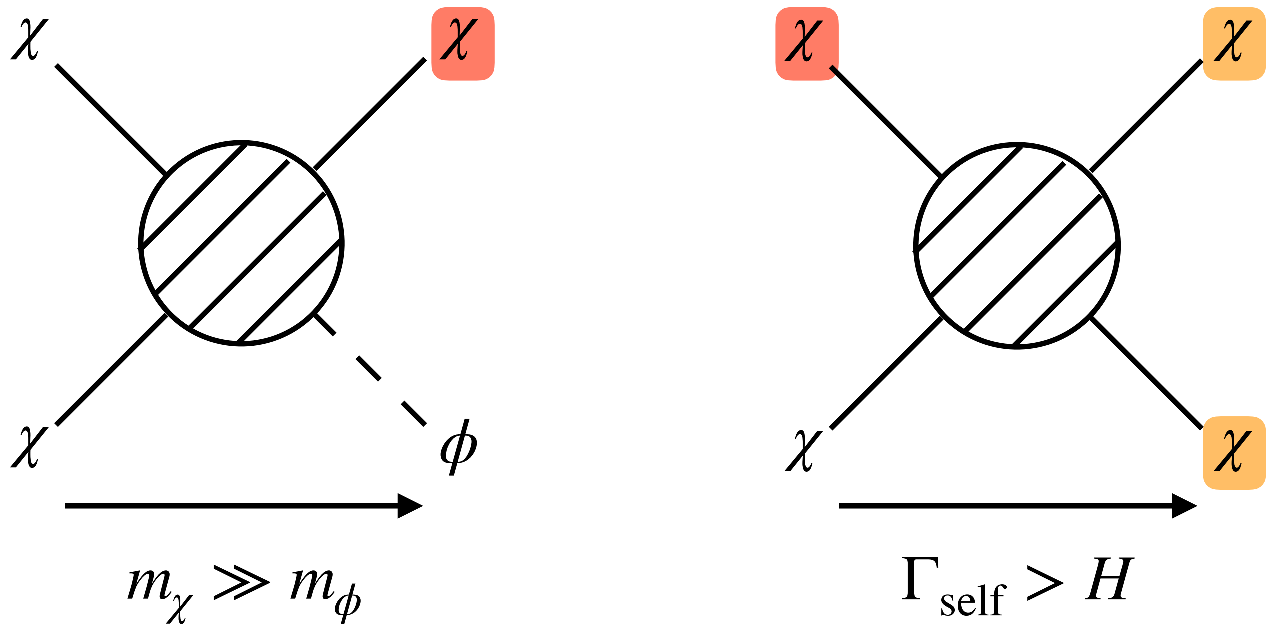
semi-annihilation



*If $T_\chi = T$ is guaranteed for some reason, the freeze-out proceeds as usual.*

F. D’Eramo, J. Thaler, JHEP (2010)

semi-annihilation + self-interaction of DM:



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

$T_\chi$ : DM temperature

*Semi-annihilation produce hot DM particles.*

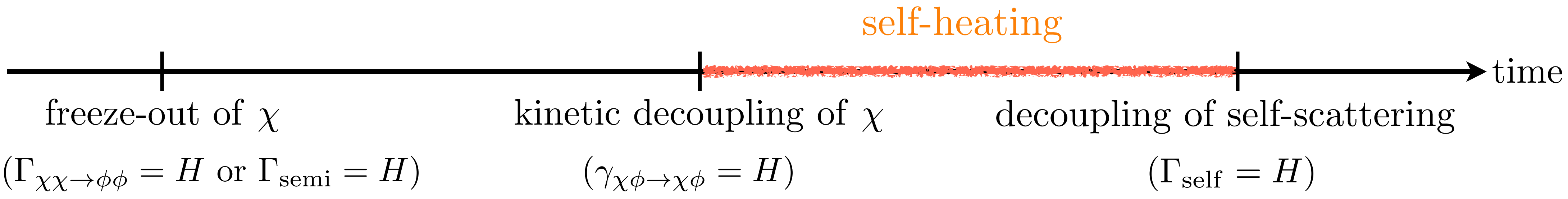
*Kinetic energy of hot DM is redistributed to others through self-interaction.*

↓

*DM temperature redshifts as* $T_\chi \propto 1/a$ *even when they are non-relativistic.*

(Semi-annihilation is special; 3 to 2 self-annihilation do not exhibit this feature.)

*Self-heating ($T_\chi \propto 1/a$) takes place between*
*kinetic decoupling and decoupling of self-interaction.*



self-heating

time

freeze-out of $\chi$

$(\Gamma_{\chi\chi\to\phi\phi} = H \text{ or } \Gamma_{\rm semi} = H)$

kinetic decoupling of $\chi$

$(\gamma_{\chi\phi\to\chi\phi} = H)$

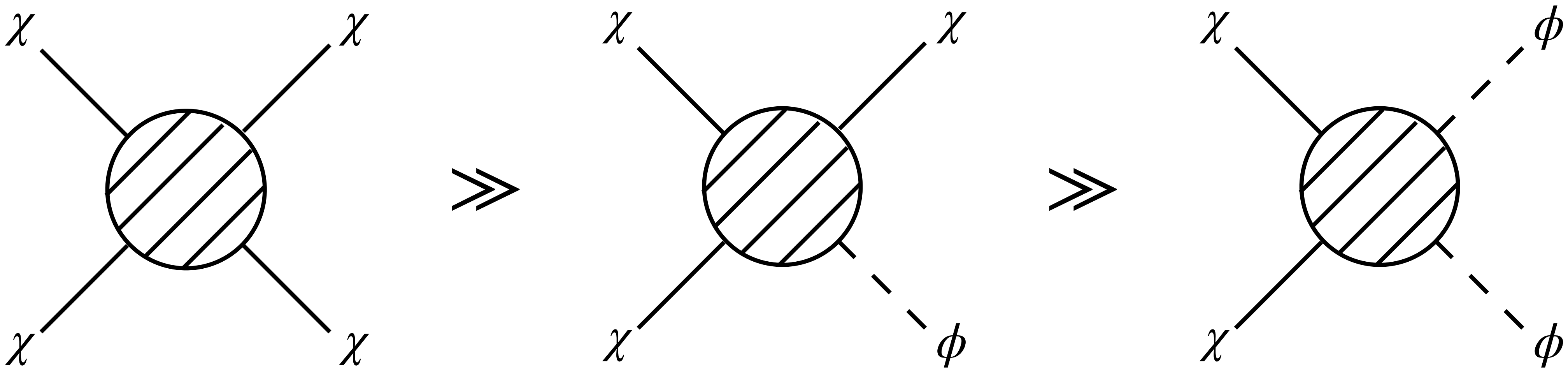
decoupling of self-scattering

$(\Gamma_{\rm self} = H)$

*Strong self-interaction prolongs the self-heating.*

*Warmness and self-interaction are interrelated!*

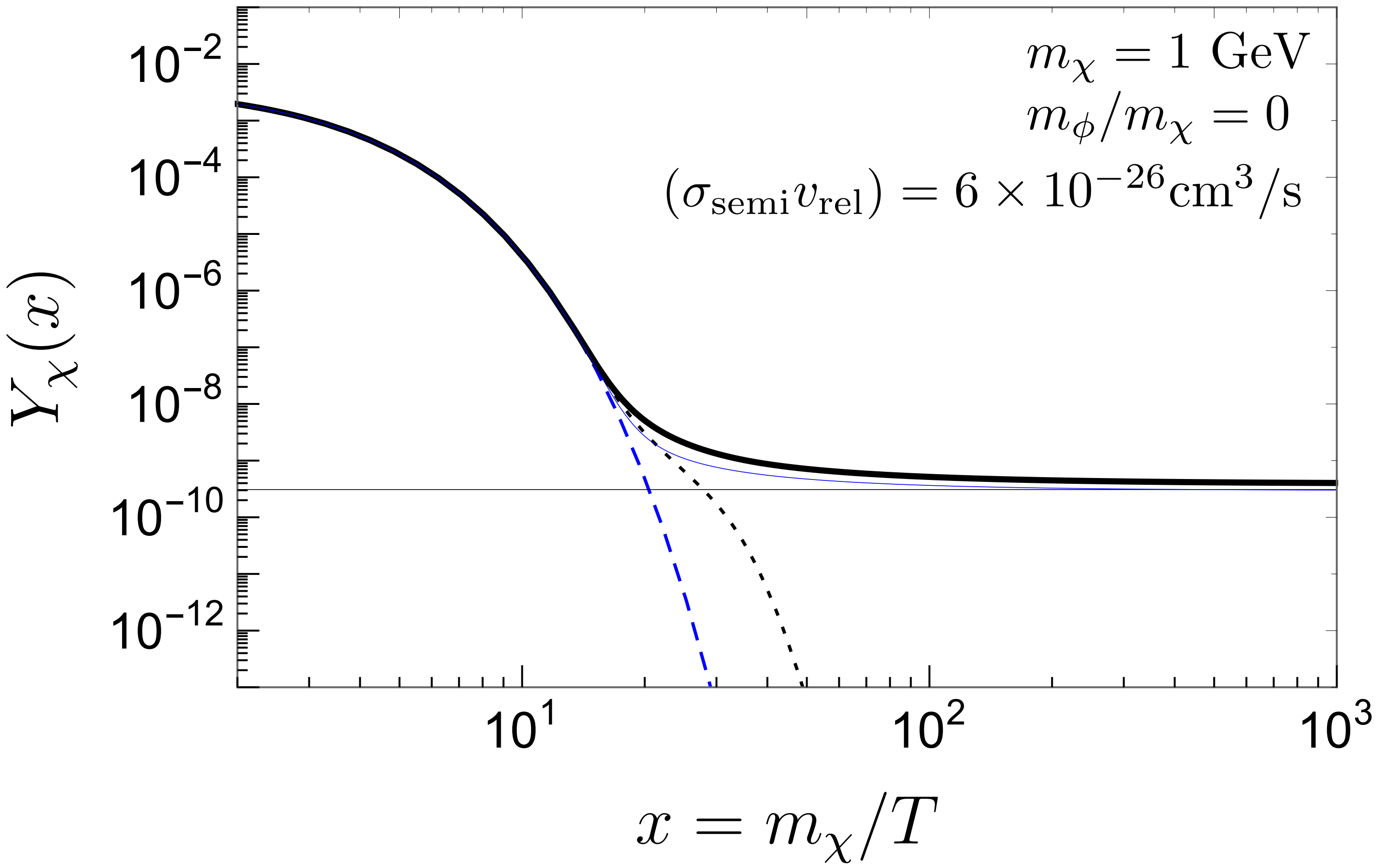
*Let us have a look at the simplest case.*



$$E_\chi \left[ \frac{\partial}{\partial t} - H p_\chi \frac{\partial}{\partial p_\chi} \right] f_\chi = C_{\mathrm{self}} \left[ f_\chi \right] + C_{\mathrm{semi}} \left[ f_\chi \right]$$

# freeze-out of DM

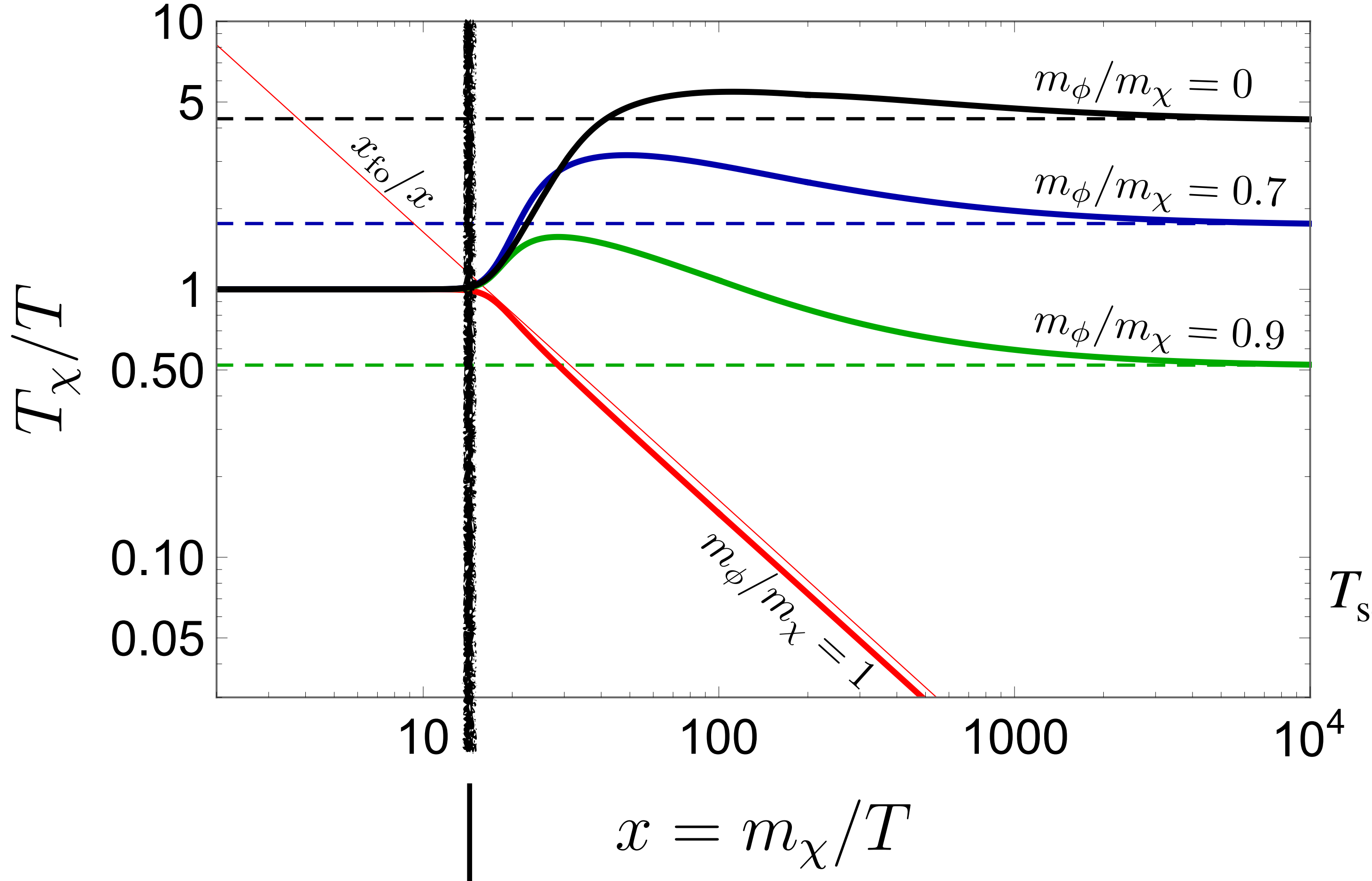
*we follow the co-evolution of DM number density and temperature.*



*Freeze-out proceeds as if "usual $(T_\chi = T)$".*

*But…*

# freeze-out of DM

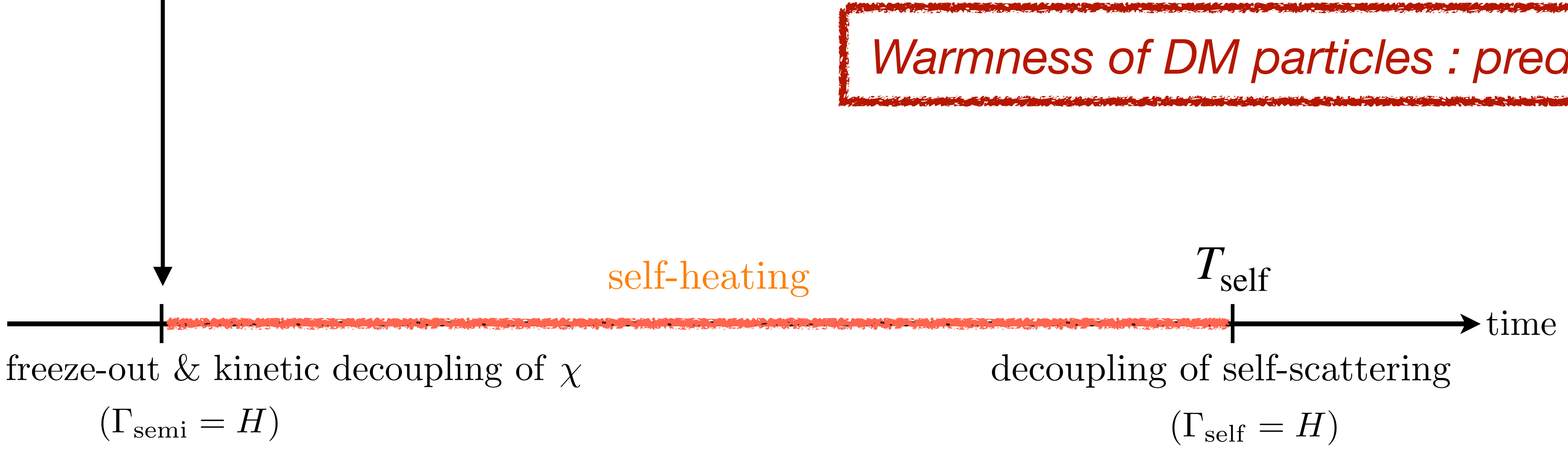


*$T_\chi \propto 1/a$ after the freeze-out!*

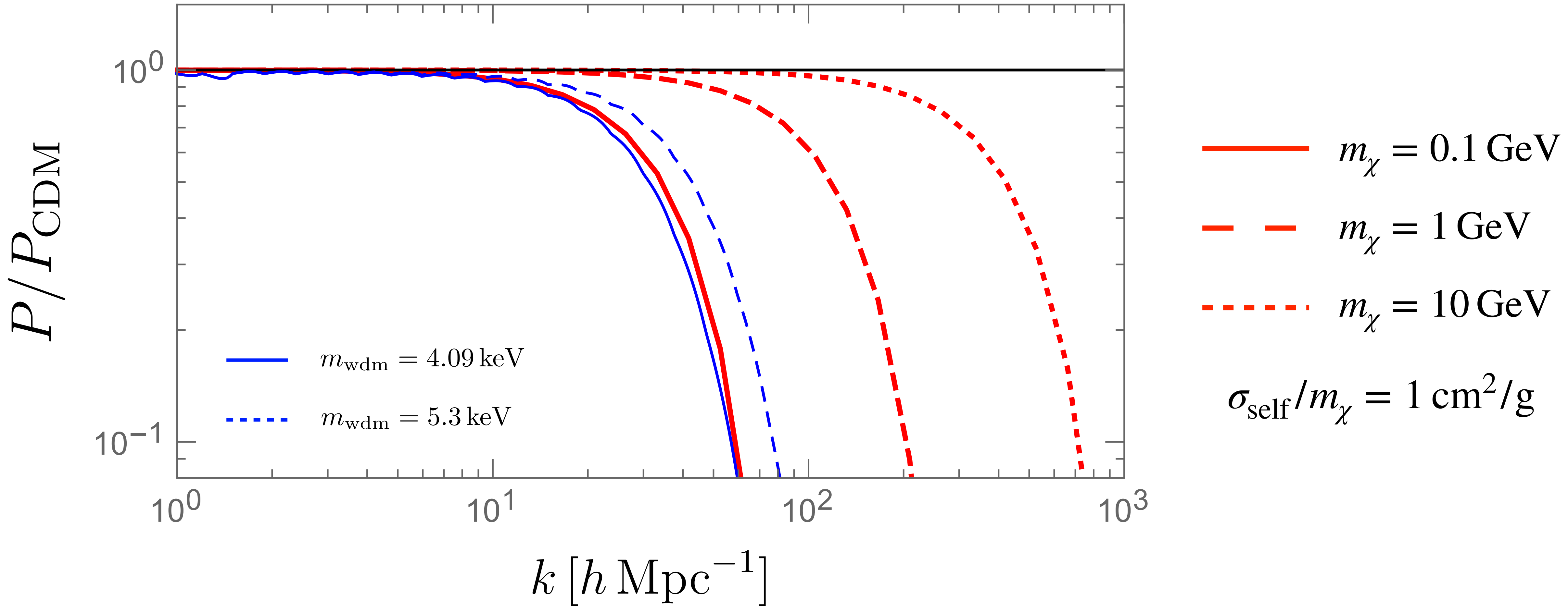
*Self-heating will continue until $T_{\rm self}$ :*

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

*Warmness of DM particles : predictions?*



# implications on small-scale structures



*suppression of density perturbation below* $k_{\rm J}^{-1}$ *at the matter-radiation equality:*

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

# *warmness ↔ self-interaction*

*thermal motion of DM particles : sub-galactic scale structure formation is suppressed*

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

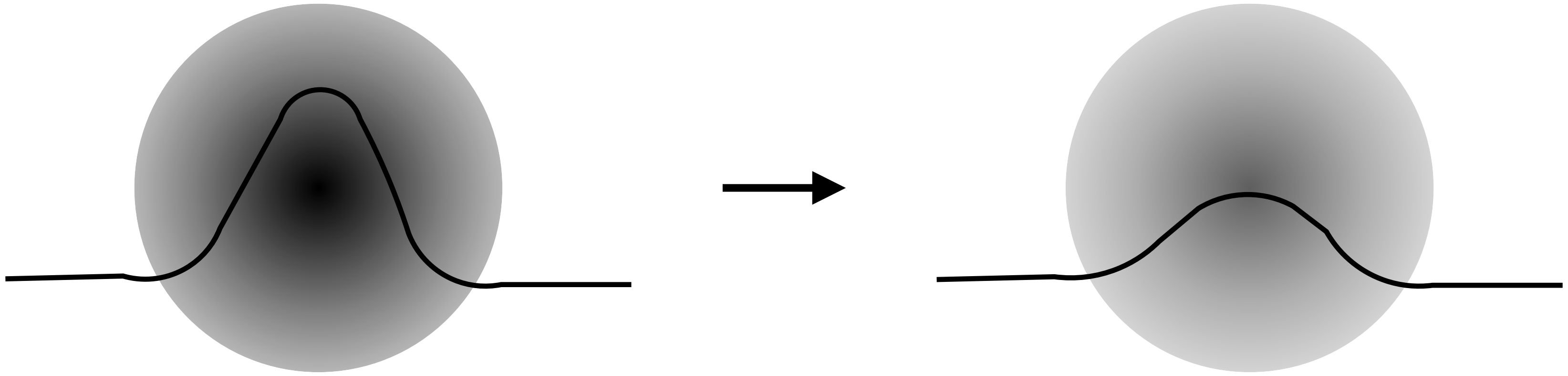
*alleviates the missing-satellites problem.*

B. Moore et. al., APJ (1999)

A.V. Kravtsov, Adv. Astro. (2010)

*such sub-galactic scale suppression is realized for* $\sigma_{\rm self}/m_\chi \sim 1\,{\rm cm}^2/{\rm g}$.

*the same self-interaction flattens the potential well of galaxies.*



*alleviates the core-cusp problem.*

B. Moore et. al., MNRAS (1999)

W.J.G. de Blok, Adv. Astro. (2010)

## decoupled sector of pion-like particles ($\chi^a$) + an axion-like particle ($\phi$)

$$\mathcal{L}_{\rm d} \supset \frac{1}{2}\left(\partial_\mu \phi\right)^2 + N_i^\dagger i\bar{\sigma}^\mu D_\mu N_i + \bar{N}_i^\dagger i\bar{\sigma}^\mu D_\mu \bar{N}_i - \left(m_N \bar{N}_i N_i + {\rm h.c.}\right)$$

$$-\frac{1}{4}H^a_{\mu\nu}H^{a\mu\nu} + \frac{\phi}{f}\frac{g_H^2}{32\pi^2}H^a_{\mu\nu}\widetilde{H}^{a\mu\nu}$$

A. Kamada et. al., PRD (2017)

$N_i$ and $\bar{N}_i$ : $N_f$-flavored vector-like pairs

$\phi$ : ALP, $f$ : ALP decay const.

$SU(N_H)$ confines and pions emerge : $SU(N_f)_V$

*stability of pions ($\chi$)*

$$\mathcal{L}_{\rm d} \supset \frac{1}{2}\left(\partial_\mu \phi\right)^2 + \mathcal{L}_{\rm chiral}$$

$$\mathcal{L}_{\rm chiral} \supset \frac{f_\chi^2}{16}{\rm Tr}\left(\partial_\mu U \partial^\mu U^\dagger\right) + \mu^3 {\rm Tr}\left(m_N \widetilde{U} + {\rm h.c.}\right)$$

$\widetilde{U} = U e^{i\phi/(N_f f)}$, $U = e^{2i\chi^a T^a/f_\chi}$, $f_\chi$ : pion decay const.

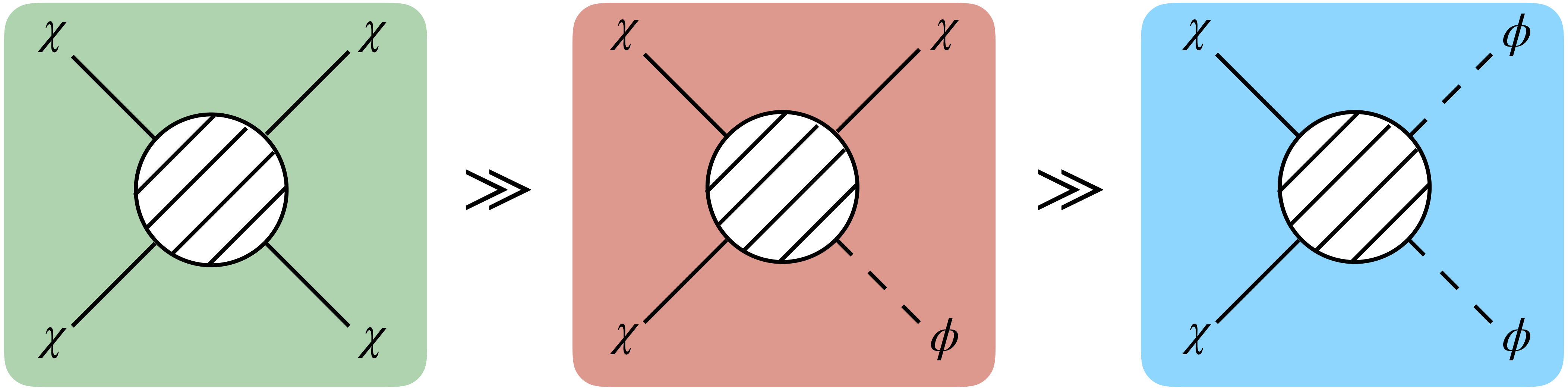
# decoupled sector of pion-like particles ($\chi^a$) + an axion-like particle ($\phi$)

self-heating

time

freeze-out & kinetic decoupling of $\chi$
$(\Gamma_{\rm semi} = H)$

decoupling of self-scattering
$(\Gamma_{\rm self} = H)$



$$\mathscr{L}_{\rm chiral} \supset \left[-\frac{1}{6f_\chi^2} r_{abcd}\left(\partial_\mu\chi^a\right)\left(\partial^\mu\chi^b\right)\chi^c\chi^d + \frac{m_\chi^2}{12f_\chi^2} c_{abcd}\chi^a\chi^b\chi^c\chi^d\right] + \frac{m_\chi^2}{6N_f f_\chi f} d_{abc}\chi^a\chi^b\chi^c\phi + \frac{m_\chi^2}{4N_f^2 f^2}\left(\chi^a\right)^2\phi^2$$

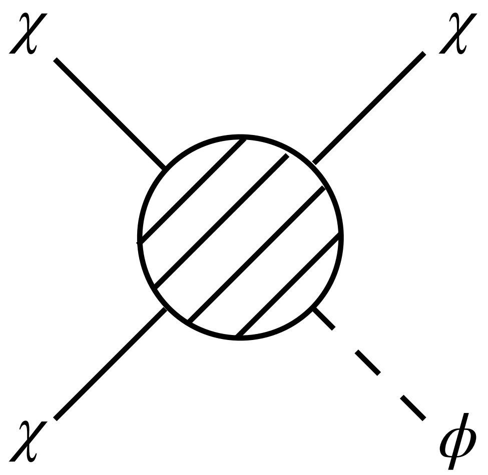
*DM interaction hierarchy is realized for* $f \gg f_\chi$

*our benchmark :* $f \simeq 300\,\mathrm{GeV}\,,\, f_\chi \simeq 40\,\mathrm{MeV}\,,\, m_\chi \simeq 50\,\mathrm{MeV}$
$\left(N_f = 4\,, N_H = 3\right)$

# decoupled sector of pion-like particles ($\chi^a$) + an axion-like particle ($\phi$)

*indirect detection, CMB : $\phi$ should not couple to SM.*

A. Kamada et. al., PRD (2017)



*instead, $\phi$ couples to dark radiation $SU(N_X)$ :*

$$\mathscr{L}_{\rm d} \supset \frac{g_X^2}{32\pi^2}\frac{\phi}{f} X^a_{\mu\nu}\widetilde{X}^{a\mu\nu}$$

*where $X$'s form a thermal bath of $T_{\rm DR}$.*

*BBN, CMB : dark sector should never be in thermal equilibrium with SM.*

$$\mathscr{L}_{\rm d} \supset \lambda_{H\Phi}\left|\Phi\right|^2\left|H\right|^2$$

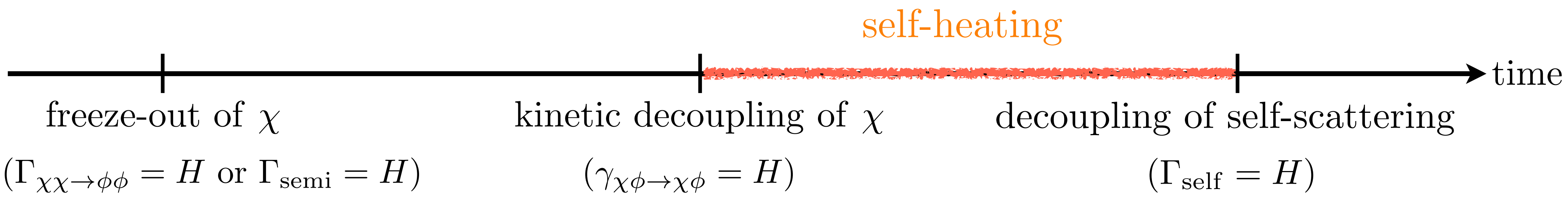
*(SSB of PQ : $\Phi = \frac{v_\Phi + \rho}{\sqrt{2}}e^{i\phi/v_\Phi}$)*

*dark sector is produced through a feeble Higgs portal coupling.*

$$\left(\frac{T_{\rm DR}}{T_{\rm SM}}\right)_{\rm ew} \simeq 0.5\left(\frac{\lambda_{H\Phi}}{2.2\times10^{-6}}\right)^{1/2}\left(\frac{106.75}{g_{*,\,\rm SM,\,ew}}\right)^{1/8}\left(\frac{83.5}{g_{*,\,\rm DR,\,ew}}\right)^{1/4}$$

# Summary

*When DM particles semi-annihilate and self-interact, self-heating takes place in the early universe.*



self-heating

time

freeze-out of $\chi$

$(\Gamma_{\chi\chi\to\phi\phi} = H \text{ or } \Gamma_{\text{semi}} = H)$

kinetic decoupling of $\chi$

$(\gamma_{\chi\phi\to\chi\phi} = H)$

decoupling of self-scattering

$(\Gamma_{\text{self}} = H)$

*During the self-heating, $T\chi \propto 1/a$.*

*Stronger self-interaction means warmer DM particles.*

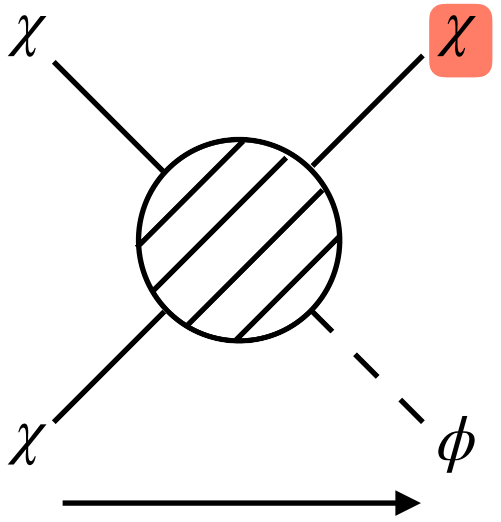
*For $\sigma_{\text{self}}/m_\chi \sim 1\,\text{cm}^2/\text{g}$, sub-galactic scale structure formation is suppressed.*

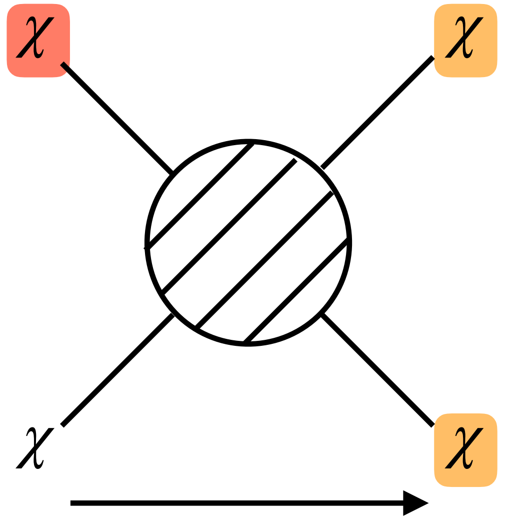
*Such strong self-interaction also flattens the inner density profiles of galaxies.*

*It would be interesting to think about implications on late time structure formation.*

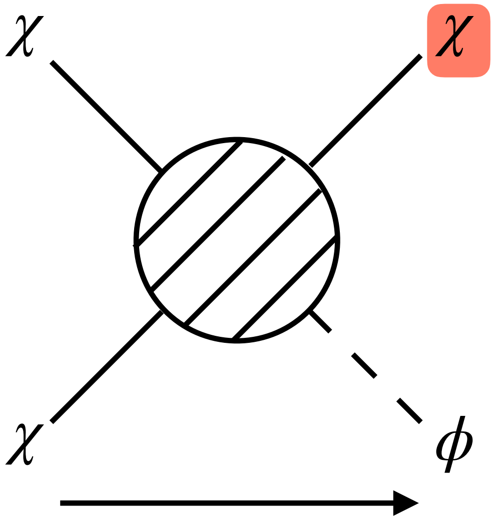
X. Chu, C. Gracia-Cely, JCAP (2018)

*Backup slides*

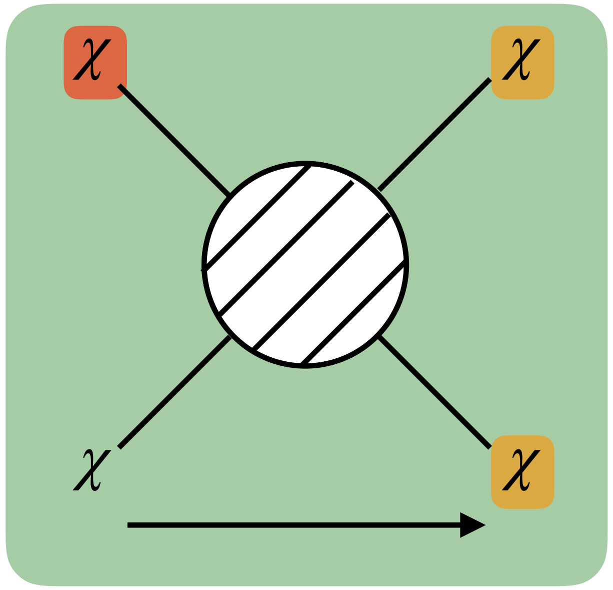




$$d\left(\rho_\chi V\right) = dQ_\chi - p_\chi dV + m_\chi dN_\chi$$



$\Gamma_{\rm self} > H$



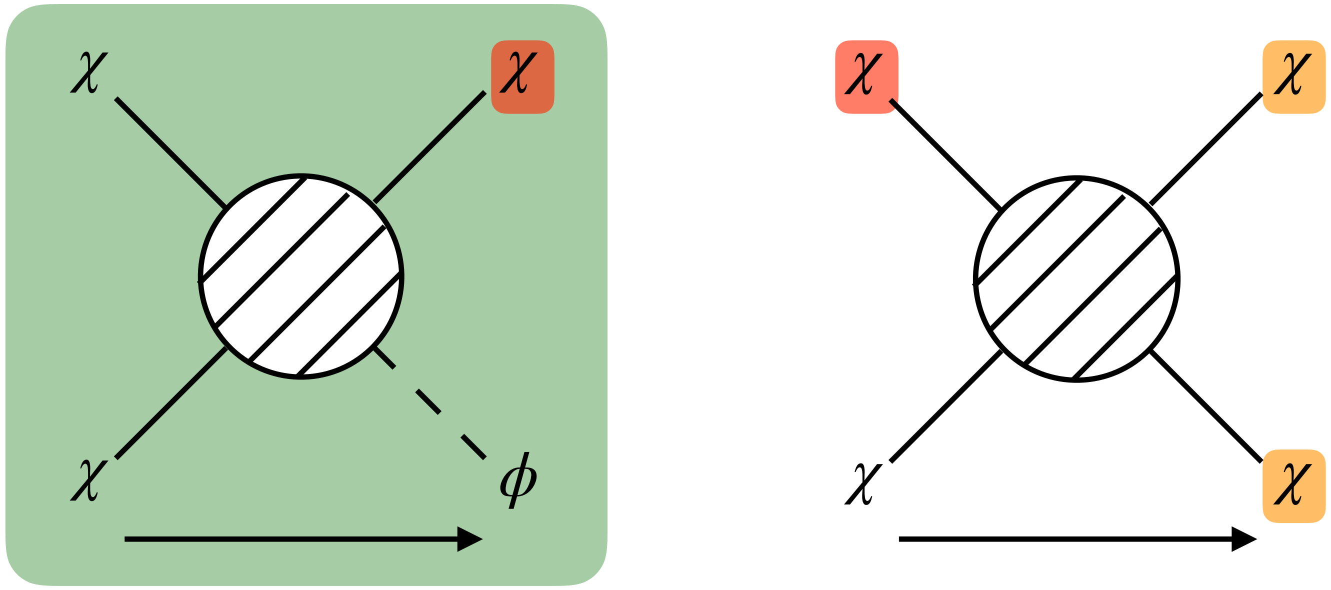
$$f_\chi = \frac{n_\chi}{n_\chi^{\rm eq}(T_\chi)} \exp(-E_\chi/T_\chi)$$

$$d\left(\rho_\chi V\right) = dQ_\chi - p_\chi dV + m_\chi dN_\chi$$

$T_\chi$ : DM temperature

$$\to d\left(\left(m_\chi + \frac{3}{2}T_\chi\right)N_\chi\right) = dQ_\chi - n_\chi T_\chi dV + m_\chi dN_\chi$$

$$E_\chi = \frac{5}{4} m_\chi$$

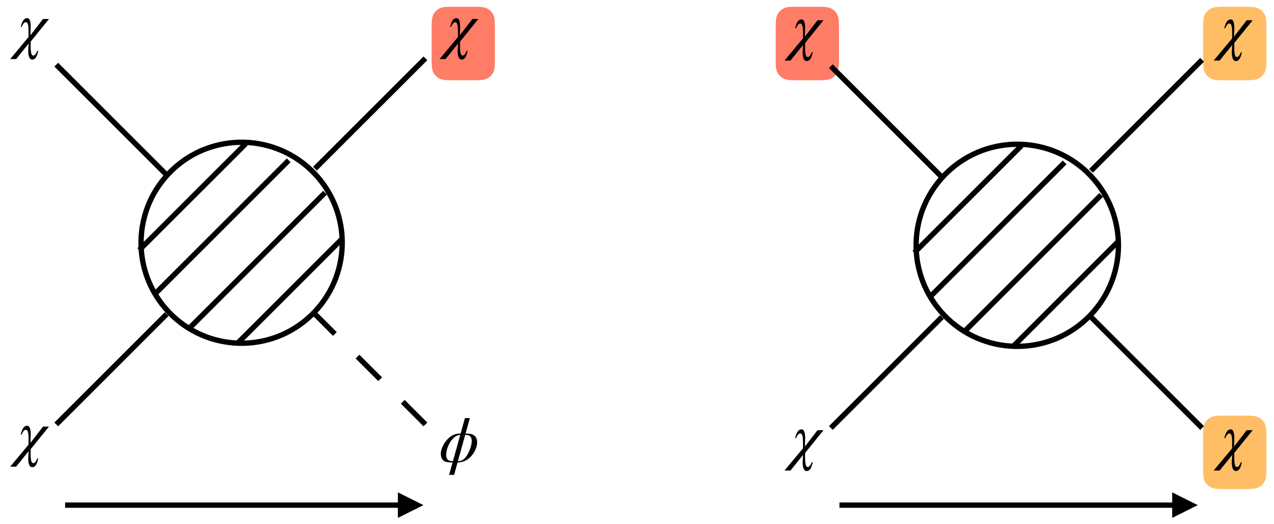


$m_\chi \gg m_\phi$

$$d\left(\rho_\chi V\right) = dQ_\chi - p_\chi dV + m_\chi dN_\chi$$

$$\to d\left(\left(m_\chi + \frac{3}{2}T_\chi\right) N_\chi\right) = -\frac{m_\chi}{4} dN_\chi - n_\chi T_\chi dV + m_\chi dN_\chi$$

$$dN_\chi \simeq -\frac{\Gamma_{\text{semi}}}{H} d \ln a$$



$$d\left(\rho_\chi V\right) = dQ_\chi - p_\chi dV + m_\chi dN_\chi$$

$$\rightarrow d\ln T_\chi \simeq \left(-2 + \frac{1}{6}\frac{m_\chi}{T_\chi}\underset{\propto 1/a}{\frac{\Gamma_{\text{semi}}}{H}}\right) d\ln a$$

*solution exists when* $T_\chi \propto 1/a$

(Semi-annihilation is special; 3 to 2 self-annihilation do not exhibit this feature.)

$$\mathscr{L}_{\rm d} = \left|\partial_\mu \Phi\right|^2 - V(|\Phi|^2) + N^\dagger i\bar{\sigma}^\mu D_\mu N + \bar{N}^\dagger i\bar{\sigma}^\mu D_\mu \bar{N} - \left(m_N \bar{N}N + {\rm h.c.}\right)$$

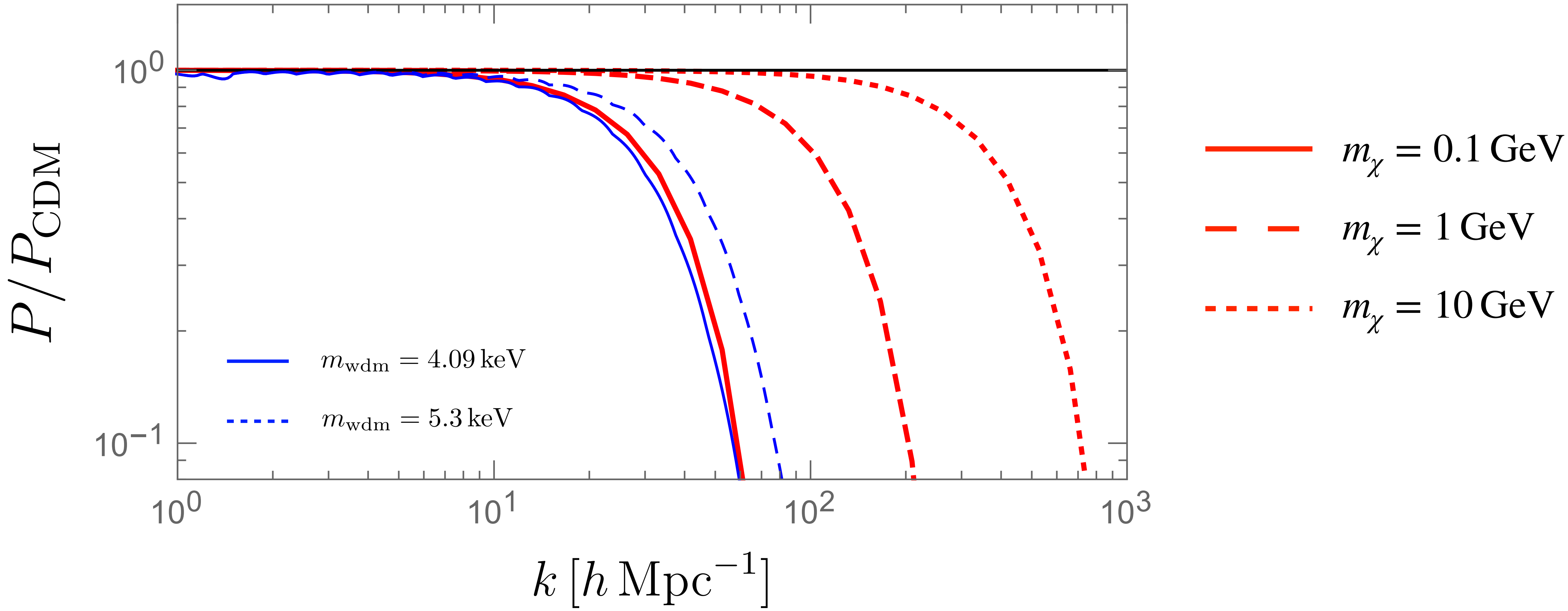
$$+Q^\dagger i\bar{\sigma}^\mu D_\mu Q + \bar{Q}^\dagger i\bar{\sigma}^\mu D_\mu \bar{Q} + L^\dagger i\bar{\sigma}^\mu D_\mu L + \bar{L}^\dagger i\bar{\sigma}^\mu D_\mu \bar{L} - \Phi\left(y_Q Q\bar{Q} + y_L L\bar{L} + {\rm h.c.}\right)$$

$$-\frac{1}{4}H^a_{\ \mu\nu}H^{a\mu\nu} - \frac{1}{4}X^a_{\ \mu\nu}X^{a\mu\nu} + \theta_H \frac{g_H^2}{32\pi^2} H^a_{\ \mu\nu}\widetilde{H}^{a\mu\nu} + \theta_X \frac{g_X^2}{32\pi^2} X^a_{\ \mu\nu}\widetilde{X}^{a\mu\nu}$$

| | SU($\mathrm{N}_H$) | SU($\mathrm{N}_X$) | U(1)$_{\rm PQ}$ |
|---|---|---|---|
| $Q$ | $\square$ | 1 | $-1/2$ |
| $\bar{Q}$ | $\bar{\square}$ | 1 | $-1/2$ |
| $L$ | 1 | $\square$ | $-1/2$ |
| $\bar{L}$ | 1 | $\bar{\square}$ | $-1/2$ |
| $N$ | $\square$ | 1 | 0 |
| $\bar{N}$ | $\bar{\square}$ | 1 | 0 |
| $\Phi$ | 1 | 1 | 1 |

TABLE I: Gauge charges of matter contents.

# cosmological linear perturbations



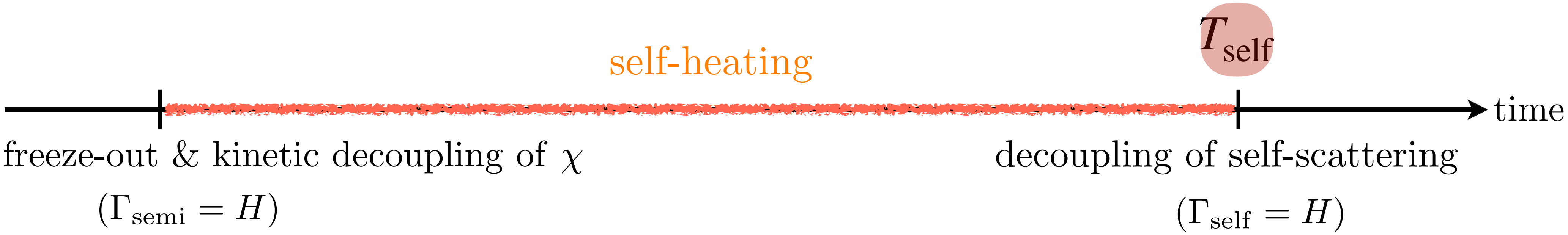
*correspondence to WDM mass:*

$$\frac{m_{\rm wdm}}{5.3\,{\rm keV}} \simeq \alpha \left(\frac{m_\chi}{1\,{\rm GeV}}\right)^{3/8} \max\left(1, \sqrt{\frac{T_{\rm self}}{T_{\rm eq}}}\right)^{3/4} \left(\frac{1{\rm cm}^2/{\rm g}}{\sigma_{\rm self}/m_\chi}\right)^{1/4} \left(\frac{T_\chi}{T}\right)_{\rm asy}^{-3/8}$$

# implications on small-scale structures

*suppression of density perturbation below* $k_J^{-1}$ *at the matter-radiation equality:*

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



$T_{\rm self}$

self-heating

time

freeze-out & kinetic decoupling of $\chi$

$(\Gamma_{\rm semi} = H)$

decoupling of self-scattering

$(\Gamma_{\rm self} = H)$

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

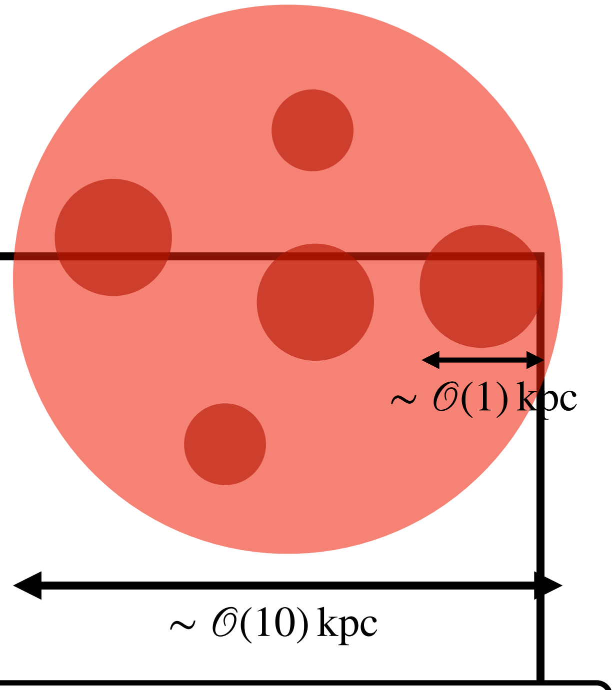
*sub-galactic scale structure formation is suppressed* for $\sigma_{\rm self}/m_\chi \sim 1\,\mathrm{cm}^2/\mathrm{g}$.

# Small-scale issues

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

$$M(<r) = 4\pi \int \rho(r) r^2 \, \mathrm{d}r$$

$$V_{\max} = \max_r \left[ V_{\mathrm{circ}}(r) \right]$$



**Missing satellites problem:**

CDM simulations predict ~O(100) number of sub-halos with $V_{\max} = 10 - 30\,\mathrm{km/s}$ in the Milky way-sized halo.

However, we observe only ~O(10).

**Inner profile :** $\rho_{\mathrm{DM}}(r) \propto r^{-\alpha}$;

$\alpha = 1$ **: Cusp (ΛCDM)**

$\alpha < 1$ **: Cored (observation)**

**Core-Cusp problem:**

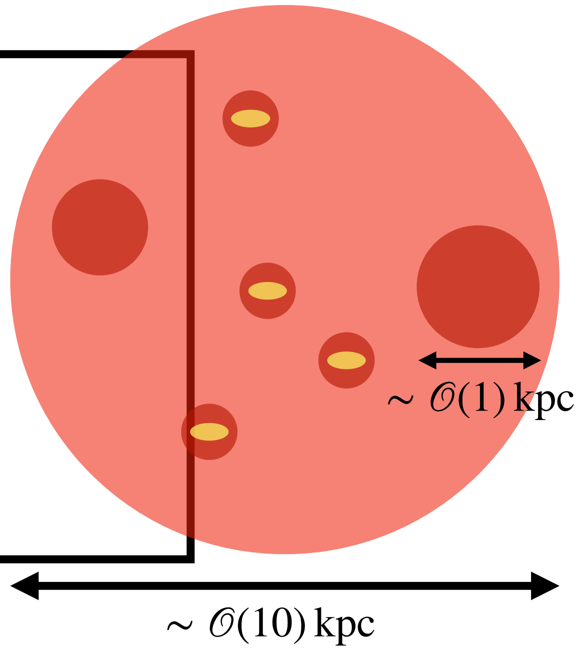
CDM simulations predict ‘cusp’ (steep) inner density profile of halos.

However, observations show ‘cored’ (less steep) profile.

**Too-big-to-fail problem:**

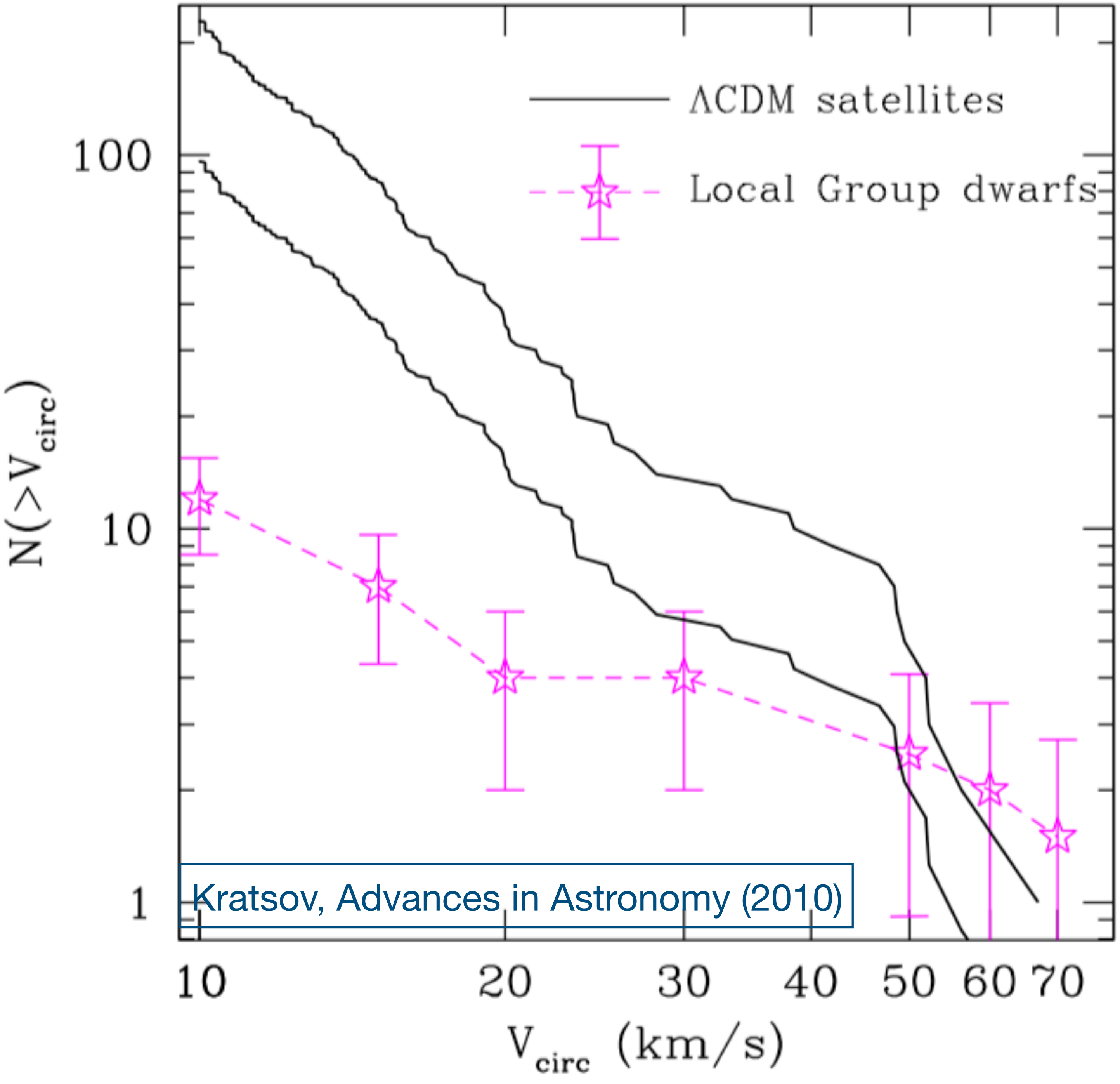
CDM simulations predict ~O(10) sub-halos with $V_{\max} > 30\,\mathrm{km/s}$.

However, we have not observed such massive sub-halos.
- “too-big-to-fail to form stars?”

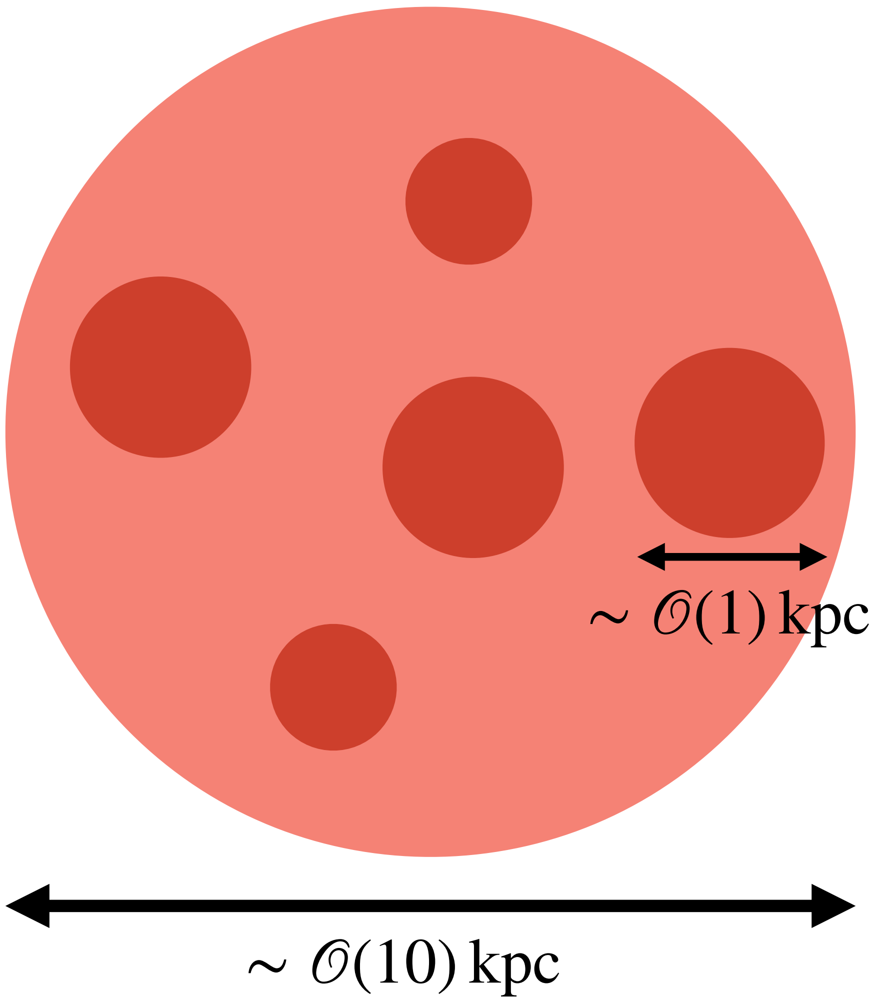


# Small-Scale issues I: Missing-satellite problem

**N-body simulations in the ΛCDM model:**
**predicts O(10) times more dwarf satellite galaxies than the observed number.**



Kratsov, Advances in Astronomy (2010)



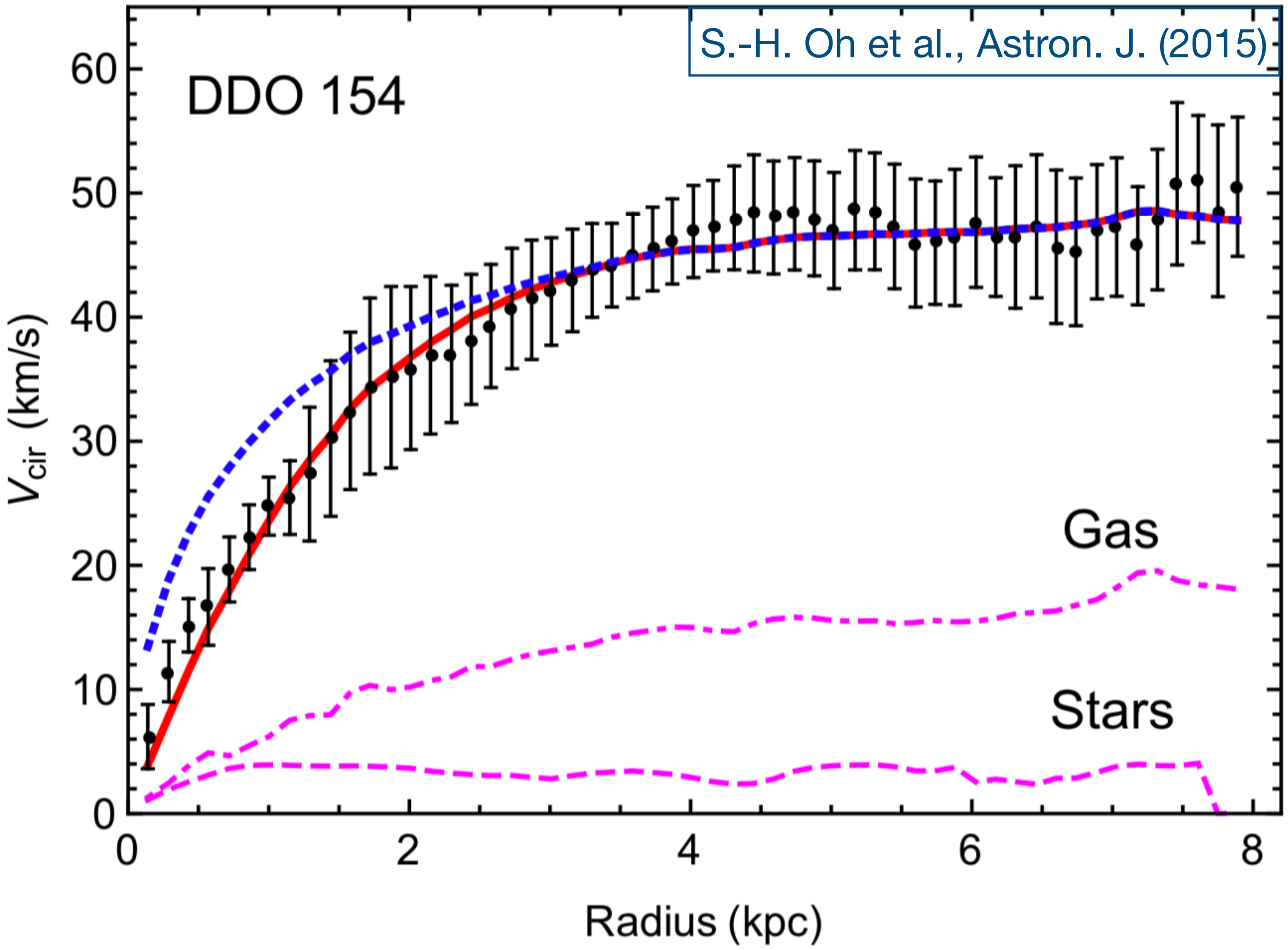
$$V_{\rm circ}^2 = \frac{GM(<r)}{r}$$

$$M(<r) = 4\pi \int \rho(r) r^2\,\mathrm{d}r$$

$$V_{\max} = \max_r \left[V_{\rm circ}(r)\right]$$

# Small-Scale issues II: Core-Cusp problem

**N-body simulations for DM halos in the ΛCDM model:**
predicts universal cusp(NFW) profile of halos;
**observation shows a cored inner profile rather than cusp**.



S.-H. Oh et al., Astron. J. (2015)

**NFW profile :**

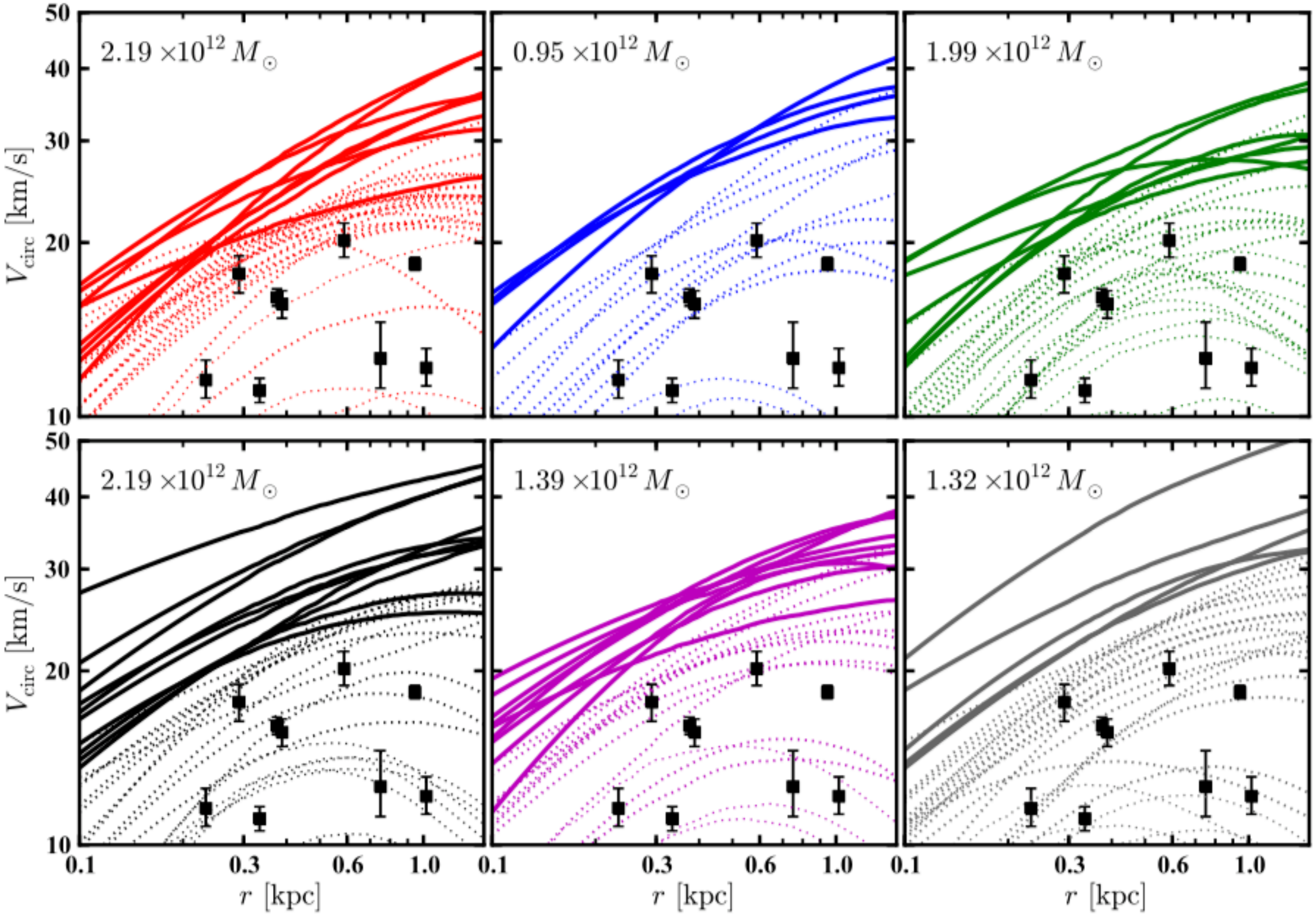
$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

**Inner profile :** $\rho_{\mathrm{DM}}(r) \propto r^{-\alpha}$ **;**

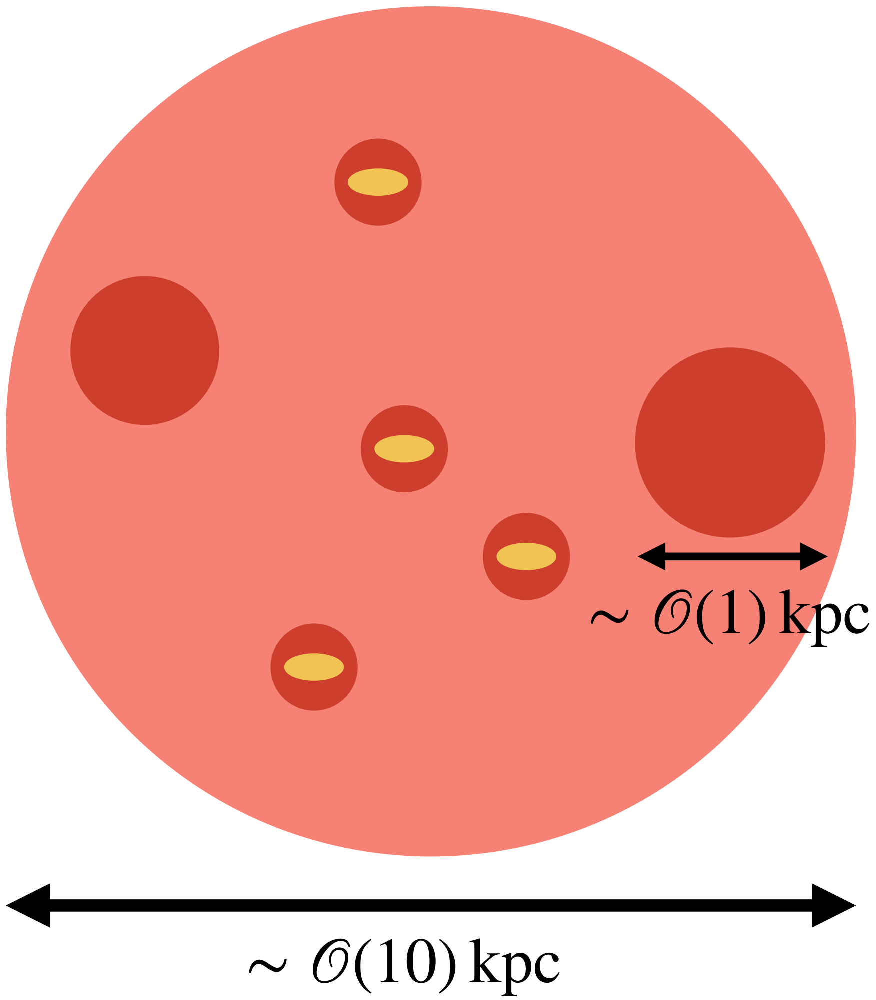
$\alpha = 1$ **: Cusp (ΛCDM)**

$\alpha < 1$ **: Cored (observation)**

# Small-Scale issues III: Too-big-too-fail problem



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



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

**N-body simulations in the ΛCDM model:**
**~10 of the most massive Galactic sub-halos have no observational counterparts.**

**<u>Common ground with the core-cusp problem:</u>**
**Massive sub-halos do host galaxies,**
**but their density profile is much shallower than the one predicted in ΛCDM.**