Strongly-interacting massive particle and dark photon in the era of intensity frontier

Ayuki Kamada (IBS-CTPU)

기초과학연구원
Institute for Basic Science

Based on
AK, Masaki Yamada, and Tsutomu T. Yanagida, arXiv:2004.13966

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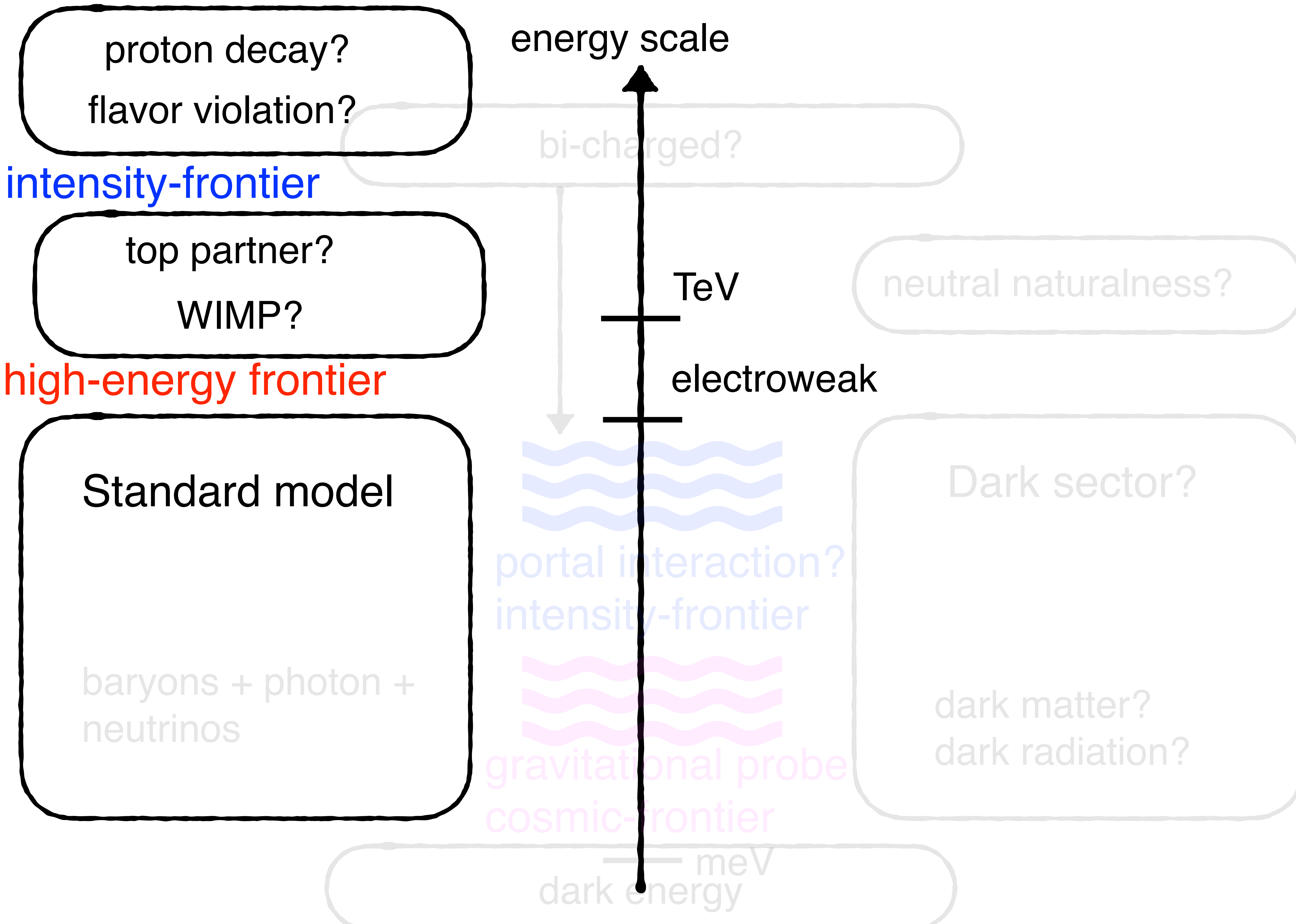
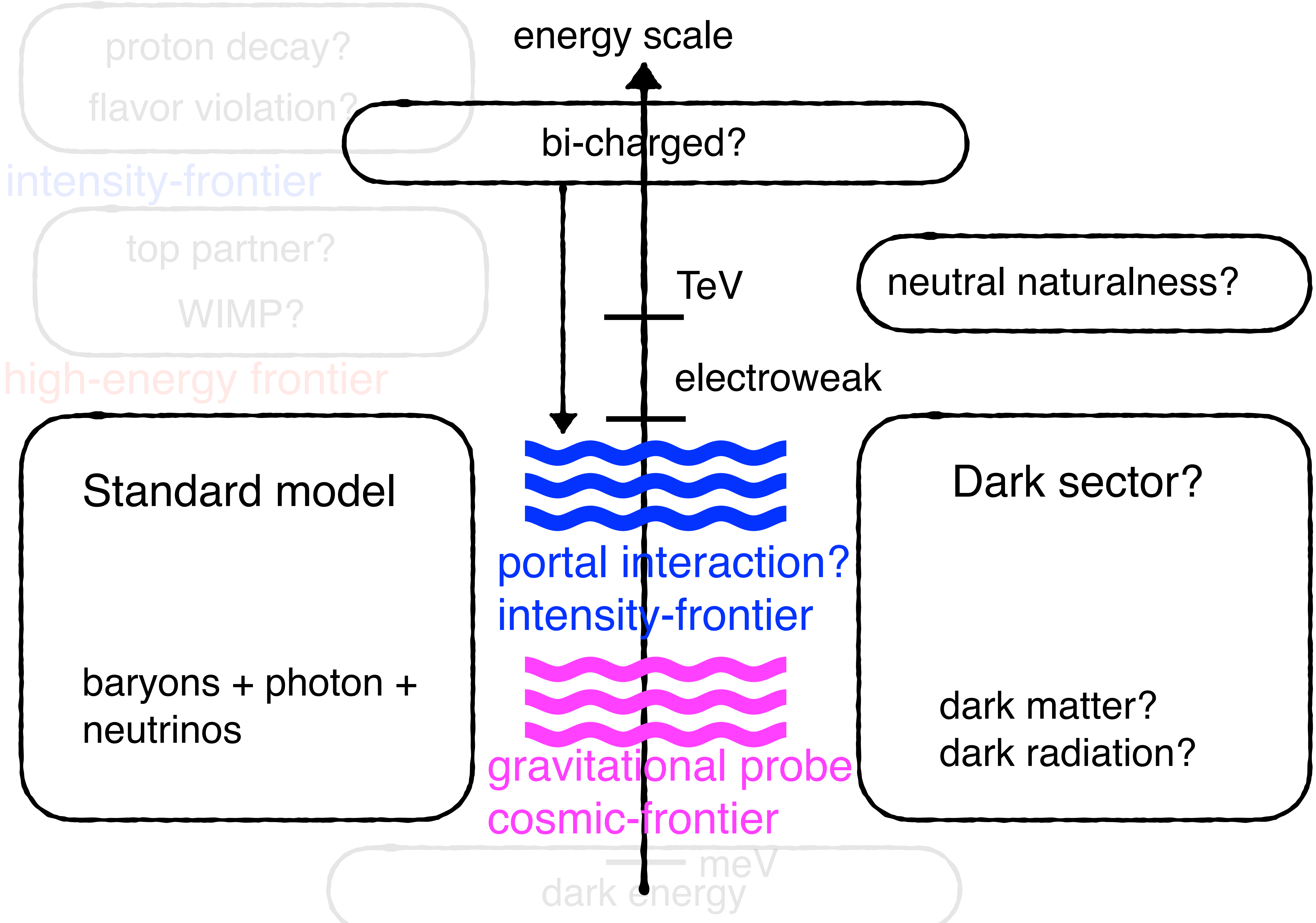
High-energy physics



High-energy? physics (this talk)



Intensity frontier

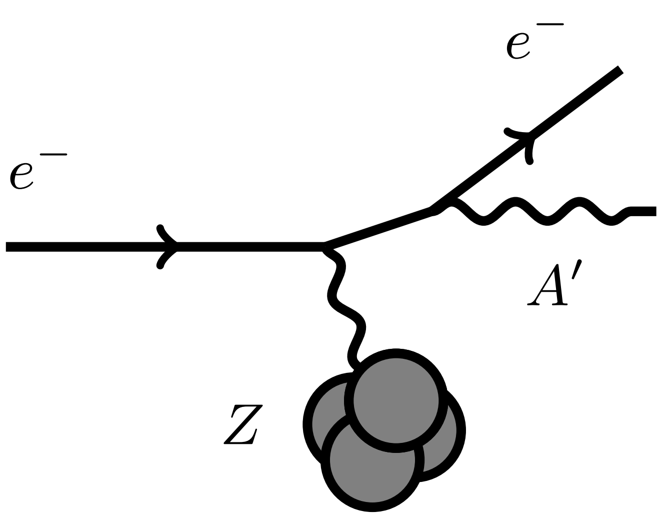
Dark photon portal $\frac{\epsilon_Y}{2} Y^{\mu\nu} F'_{\mu\nu}$ $\epsilon_Y \cos\theta_W = \epsilon$ $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$

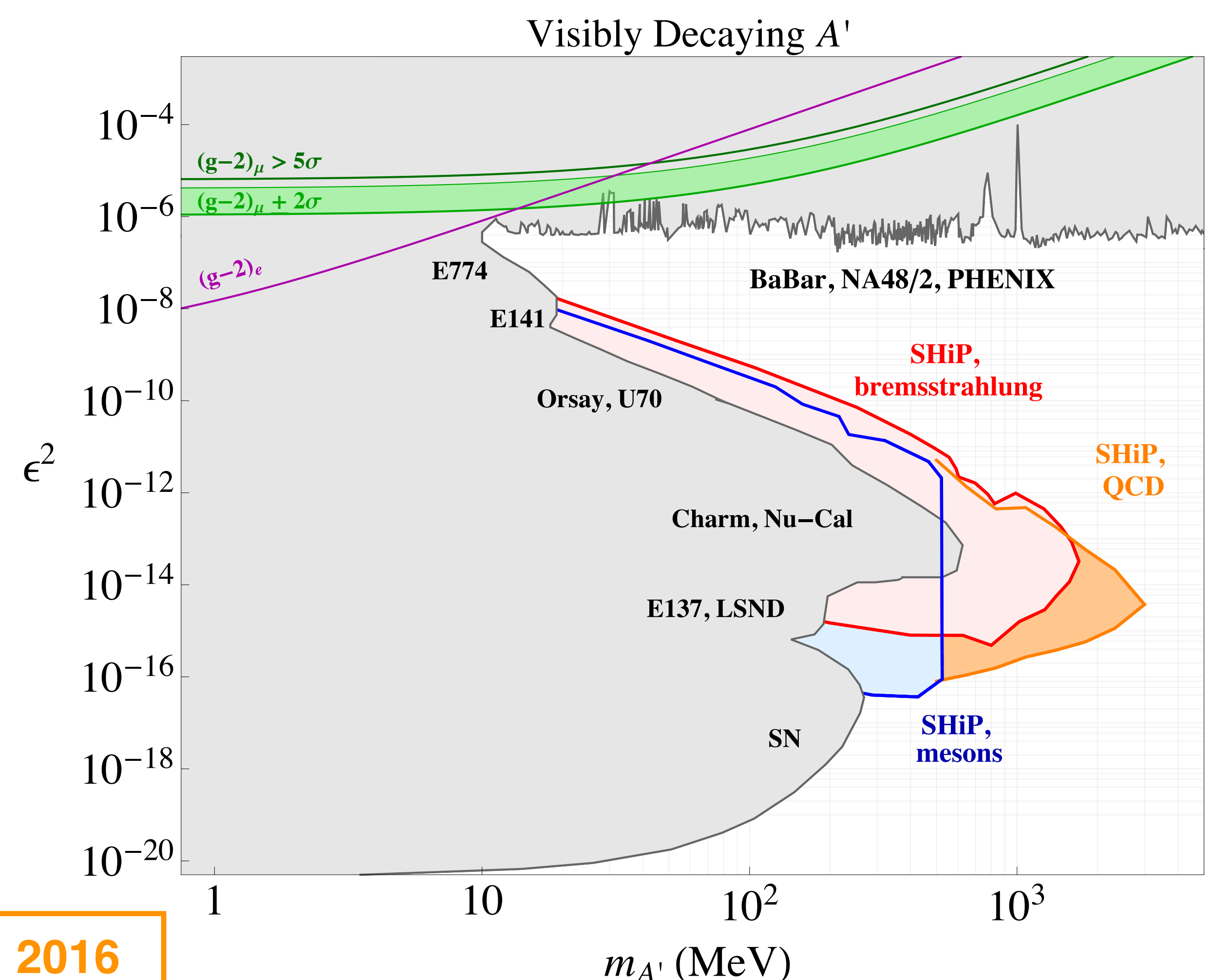
- kinetic mixing between the hyper-charge gauge boson and dark photon

- SM particles couple to dark photon $\epsilon e j^\mu_e A'_\mu$ (integration by parts)

Beam-dump experiment (visible) e.g., CHARM, E137, SHiP…

target shield detector





$A' \rightarrow$ SM

SHiP collaboration, Rep. Prog. Phys., 2016

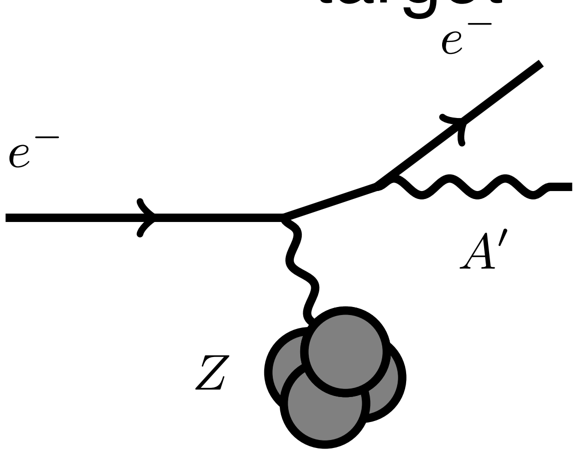
Sub-GeV DM search

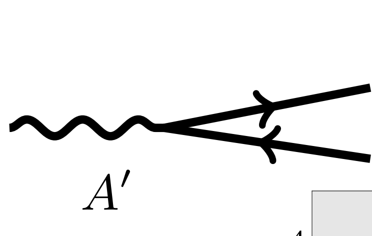
Dark photon portal to sub-GeV dark matter

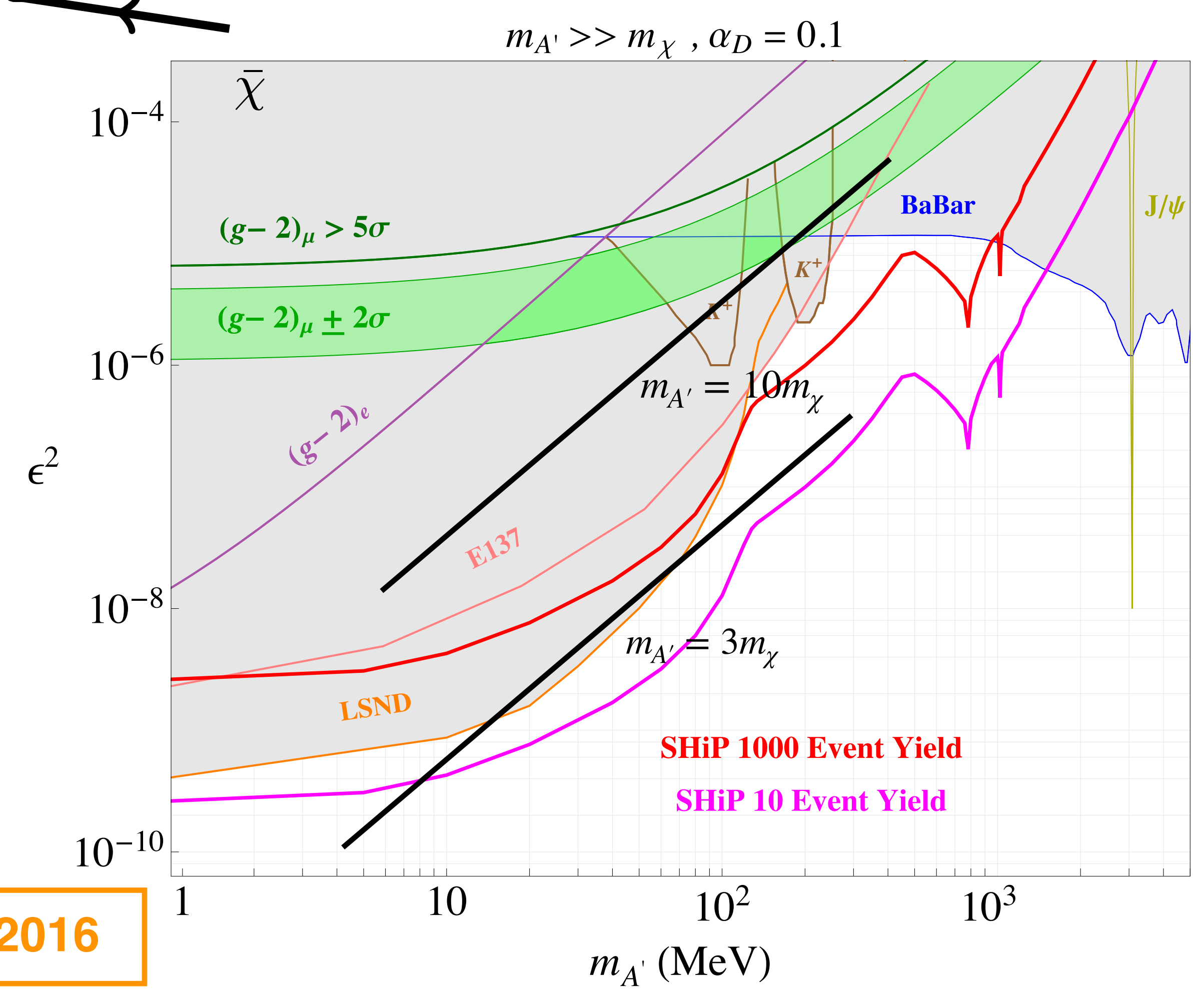
- SM and DM particles couple to dark photon $(\epsilon e j_e^\mu + e_D j_{eD}^\mu) A'_\mu$
- small kinetic mixing → correct relic abundance

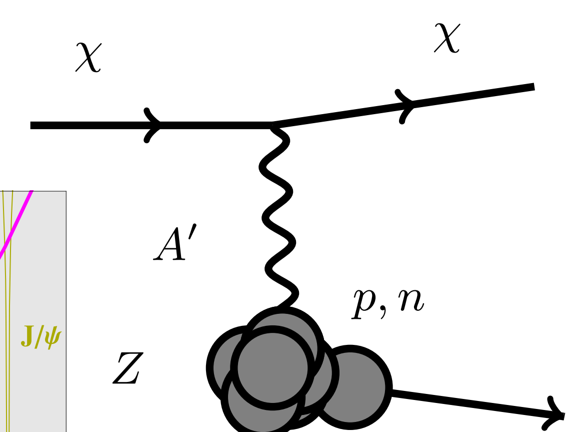
Beam-dump experiment (invisible) e.g., E137, LSND, SHiP…

target shield detector







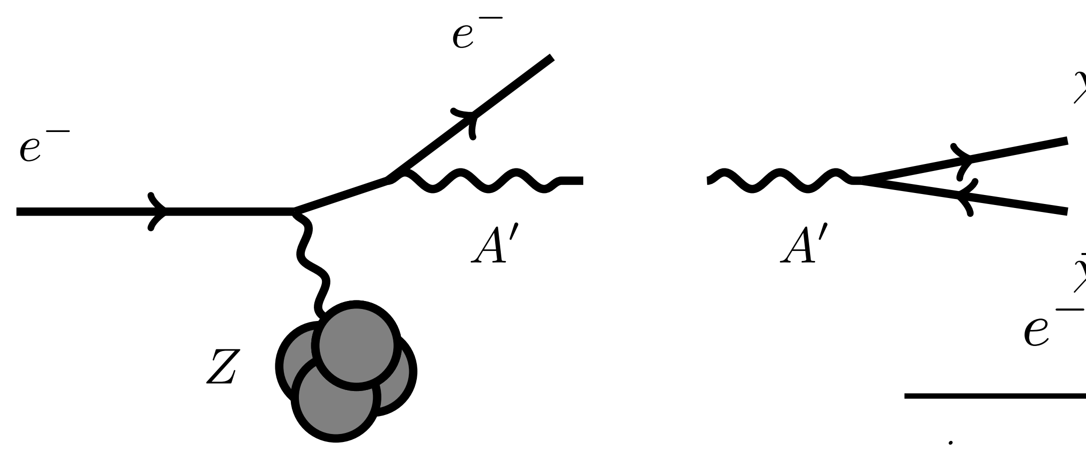


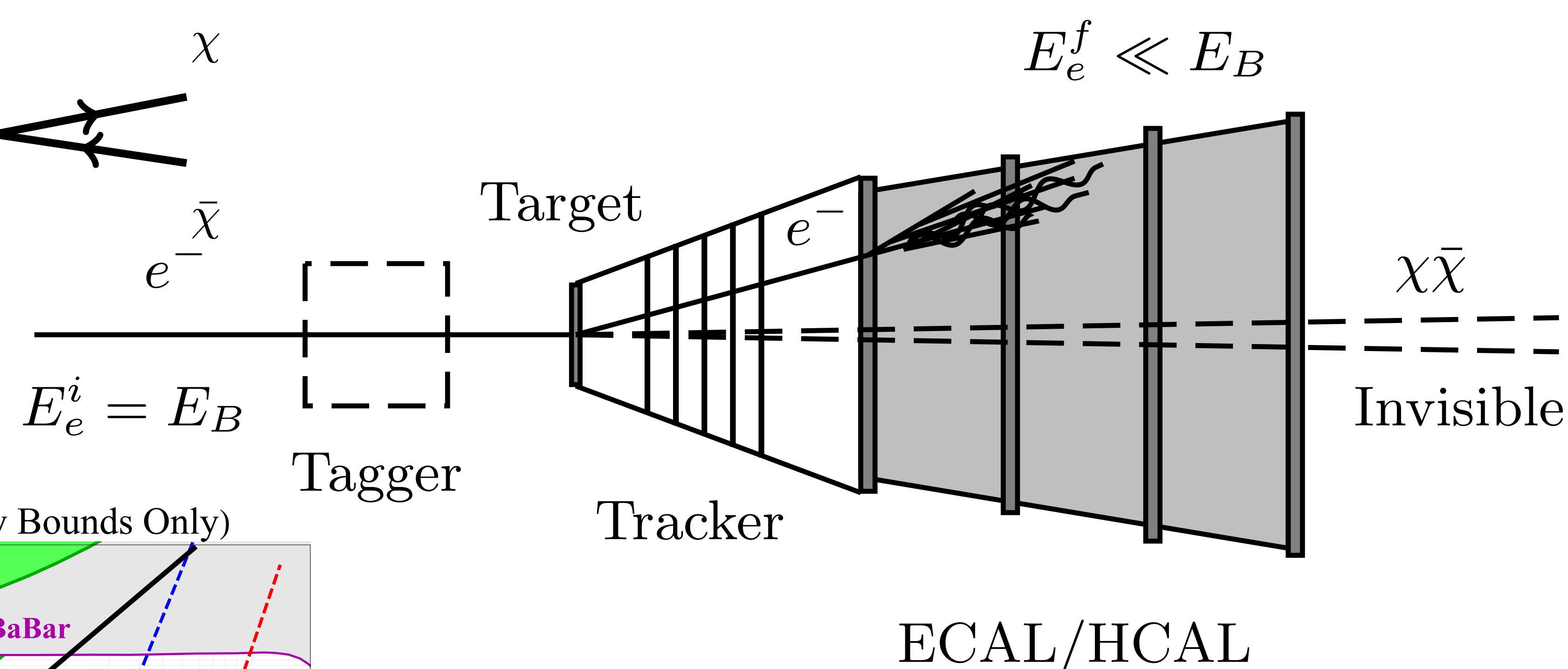
Izaguirre, Krnjaic, Schuster, and Toro, PRD, 2013

SHiP collaboration, Rep. Prog. Phys., 2016

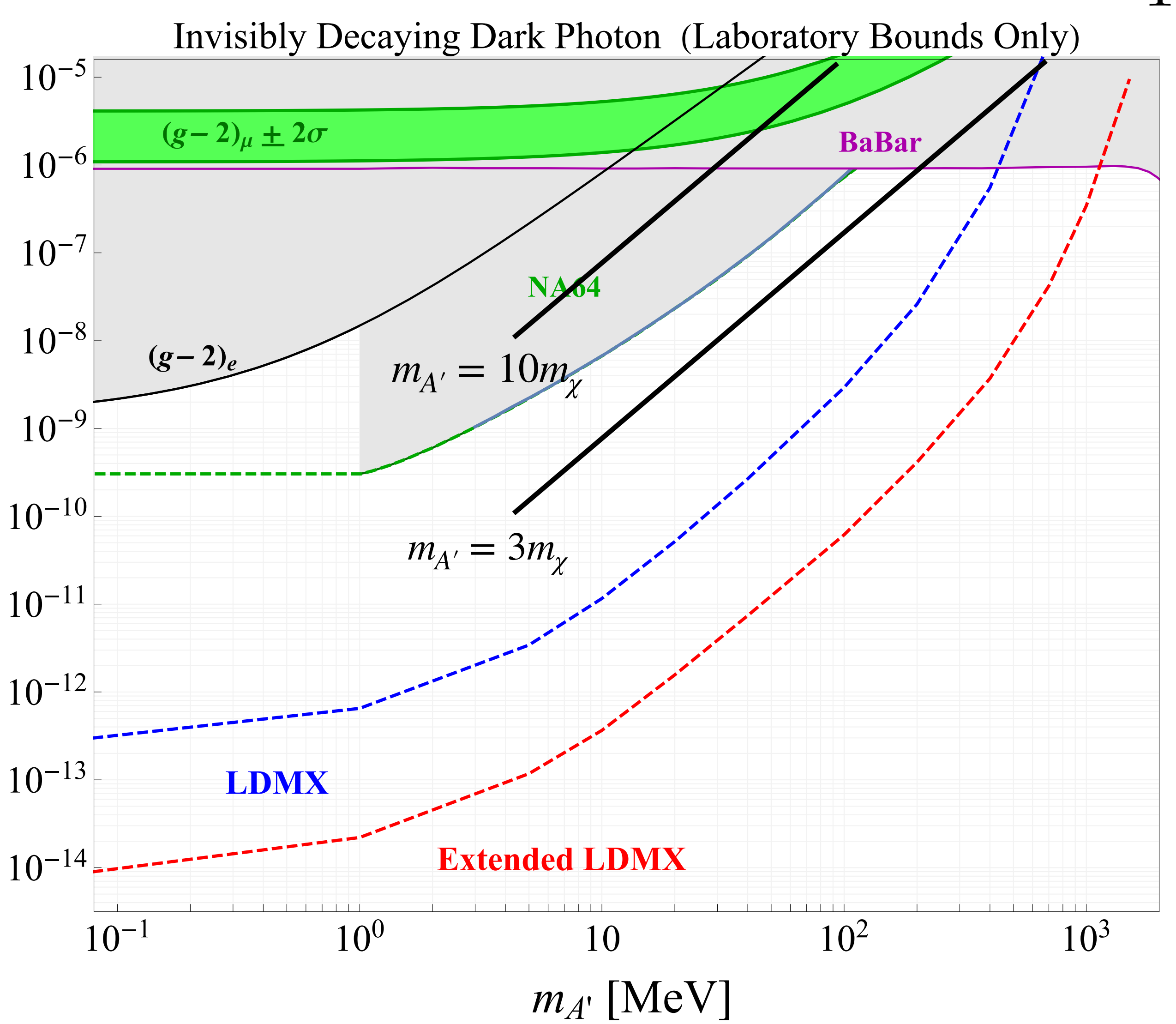
Sub-GeV DM search

Missing energy-momentum experiment e.g., LDMX …





Izaguirre, Krnjaic, Schuster, and Toro, PRD, 2015; PRL, 2015



No need for DM scattering at a detector

- applicable even if DM is neutral under $U(1)_D$, e.g., due to compositeness, i.e., undetectable in beam-dump experiments

LDMX collaboration, arXiv:1808.05219

Cosmic frontier

Small-scale issues **Bullock and Bolyan-Kolchin, Ann. Rev. Astron. Astrophys., 2018**

- tensions between observations and naive prediction of collisionless cold dark matter (CDM) on galactic scales

- may be attributed to our incomplete understanding of astrophysical processes

Self-interacting dark matter (SIDM)- interaction within a dark sector

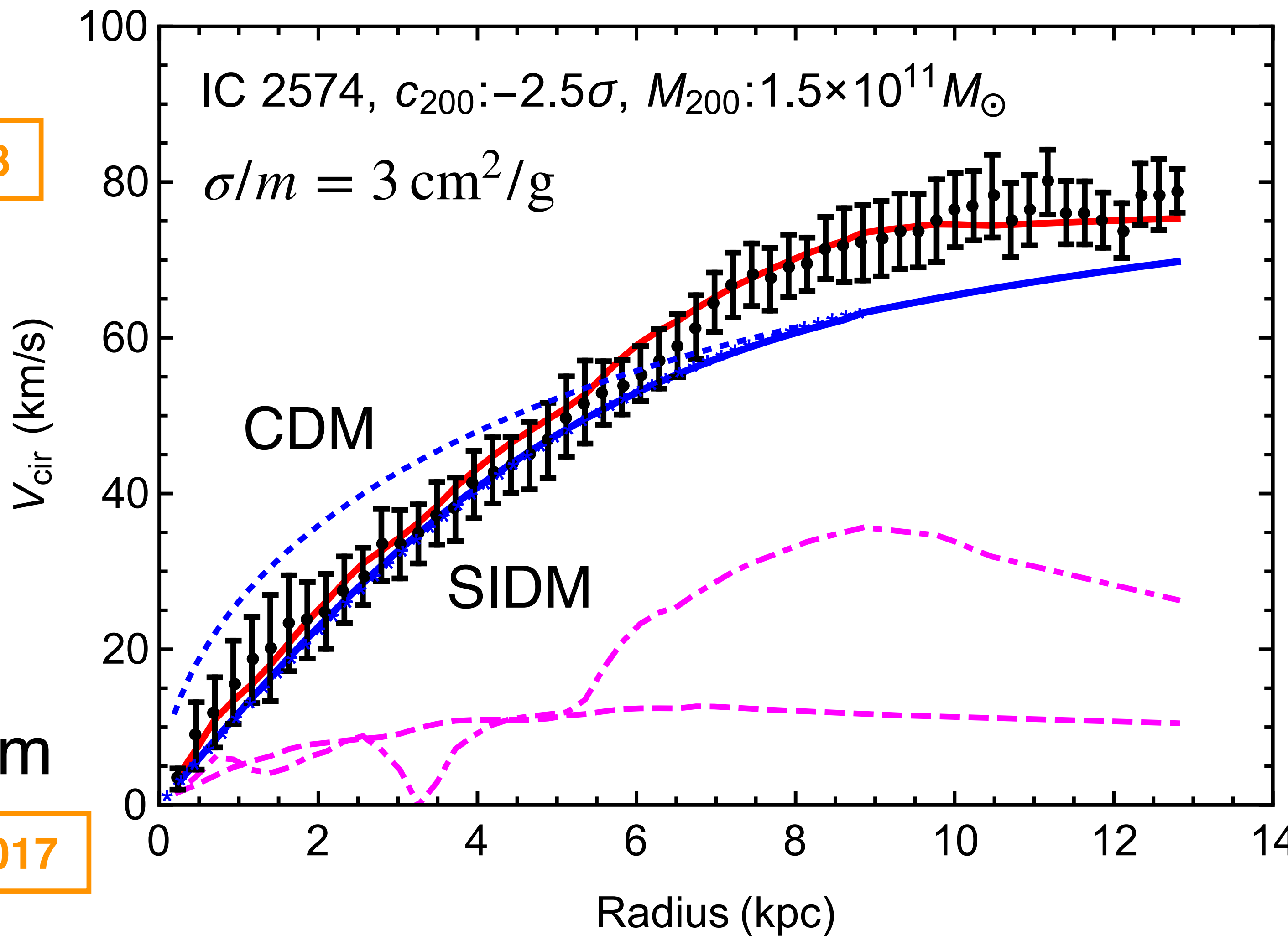
$\sigma/m \sim 1\,\mathrm{cm}^2/\mathrm{g}$

Tulin and Yu, Phys. Rept., 2018

- reduce the central mass density of a halo → core-cusp problem

- change its density profile according to the baryon distribution → diversity problem

AK, Kaplinghat, Pace, and Yu, PRL, 2017



Sub-GeV SIMP

Strongly-interacting massive particle (SIMP) $\sigma/m \sim 1\,\mathrm{cm}^2/\mathrm{g}$

- contact interaction + perturbative Unitarity → sub-GeV DM

- collect relic abundance

$\sigma/m \sim 1\,\mathrm{cm}^2/\mathrm{g}$ - strong interaction

$(\sigma_{\mathrm{ann}} v) \sim 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$ - weak interaction

- hierarchy?

- p-wave ← CMB constraints

Planck collaboration, arXiv:1807.06209

- 3→2 process of "pions" via the Wess-Zumino-Witten (WZW) term

Hochberg, Kuflik, Murayama, Volansky, and Wacker, PRL, 2015

- small kinetic mixing

- naturally fit the sub-GeV DM experiments

- "pions" charged under $U(1)_D$

Lee and Seo, PLB, 2015

Hochberg, Kuflik, and Murayama, JHEP, 2016

Berlin, Blinov, Gori, Schuster, and Toro, PRD, 2018

Our model

Integrates SIMPs and dark photon **AK, Yamada, and Yanagida, arXiv:2004.13966**

part 1

- dark sector consists of light "electron" and "monopole"
- "monopole" condensation → dark photon mass + confinement and chiral condensation of "electron" and "positron" → "pions" as SIMP DM

part 2

- "pions" are neutral under $U(1)_D$ → detectable only in LDMX-type experiments
- "pions" semi-annihilate into photon via kinetic mixing → correct relic abundance

Setup

Postulate light N_F Dirac "electrons" and scalar "monopole"

- known in SUSY gauge theories
  - Dirac quantization $e_D g_D = 2\pi\mathbb{Z}$
  - conformal field theory at UV
    - possibly explain small portal couplings
  - quantum corrections are untamed without SUSY

Seiberg and Witten, NPB, 1994; NPB, 1994

Argyres and Douglas, NPB, 1995

Argyres, Plesser, Seiberg, and Witten, NPB, 1997

- $N = 2$ SUSY

- unknown full Lagrangian description
  - "electric" A' cannot couple to "monopole" and vice versa
    - $\partial_\mu \tilde{F}'^{\mu\nu} = 0$ (Bianchi identity), but $\partial_\mu \tilde{F}'^{\mu\nu} = -g_D j^\nu_{m'}$

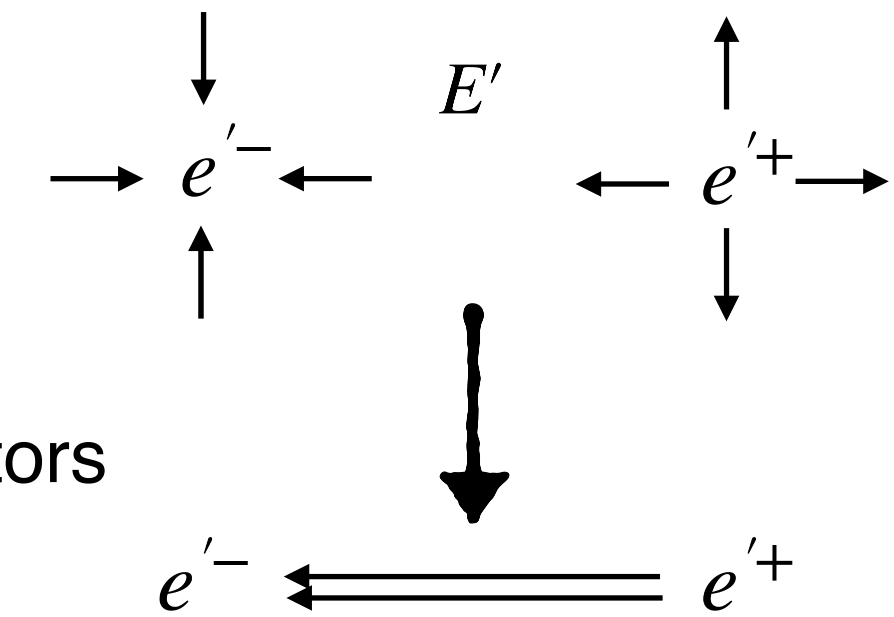
$$\tilde{F}'^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} F'_{\rho\sigma}$$

  - Lagrangian sketches physical processes
    - use naive dimensional analysis with c's $\quad c \in (0.1, 1)$

“Monopole” condensation

“Monopole” condensation

- mass of dark photon $m_{A'}$
- confine “electric” field in a local string
  - (dual) Meissner effect in superconductors
  - 1d “electric” potential $V(r) \propto r$
  - confinement of “electron” and “positron”



- local string

Nambu, PRD, 1974

- assume chiral condensation $\langle e'_i \bar{e}'_j \rangle = \Lambda^3 U_{ij} \quad U = \exp(2i\pi'/f_\pi)$
  - $SU(N_F) \times SU(N_F) \to SU(N_F)$ - unbroken to stabilize “pions” as SIMP DM
  - assume that the “pion” mass comparable with but smaller than the condensation scale Λ

$$m_{\pi'} = c_\Lambda \Lambda$$

Phenomenology

Scattering cross-section

$$\frac{\sigma_{\rm ela}}{m_{\pi'}} = \frac{(4\pi)^4 c_1 m_{\pi'}}{4\pi\Lambda^4} \simeq 2.7\,{\rm cm^2/g}\left(\frac{c_1 c_\Lambda^2}{1/(4\pi)}\right)^2 \left(\frac{m_{\pi'}}{300\,{\rm MeV}}\right)^{-3}$$

- $c_1 c_\Lambda^2 < 1/(4\pi)$ so that Unitarity holds up to $v \to c$

Coupling to dark photon - preserving $C(\pi \to \pi^T)$ and $P(\pi \to -\pi)$

- no π'-π'-A' interaction due to $SU(N_F)$ flavor symmetry
- $\frac{(4\pi)^2}{\Lambda^3}\tilde{F}'^{\mu\nu}{\rm Tr}[\pi'\partial_\mu\pi'\partial_\nu\pi']$ - invisible decay of dark photon $3m_{\pi'} < m_{A'}$
  - semi-annihilation (below)
- detectable only in LDMX-type experiments
- $\frac{(4\pi)^3}{\Lambda^5}\epsilon^{\mu\nu\rho\sigma}{\rm Tr}[\pi'\partial_\mu\pi'\partial_\nu\pi'\partial_\rho\pi'\partial_\sigma\pi']$ - subdominant for $m_{\pi'} < \Lambda$ or $N_F = 2$

Kinetic mixing

Kinetic mixing

- two C and P preserving possibility: $\frac{\epsilon'_Y}{2}Y^{\mu\nu}F'_{\mu\nu}$ or $\frac{\epsilon_Y}{2}Y^{\mu\nu}\tilde{F}'_{\mu\nu}$

- generically both exists violating P

- consider one by one for simplicity

$$\frac{\epsilon_Y}{2}Y^{\mu\nu}\tilde{F}'_{\mu\nu}$$

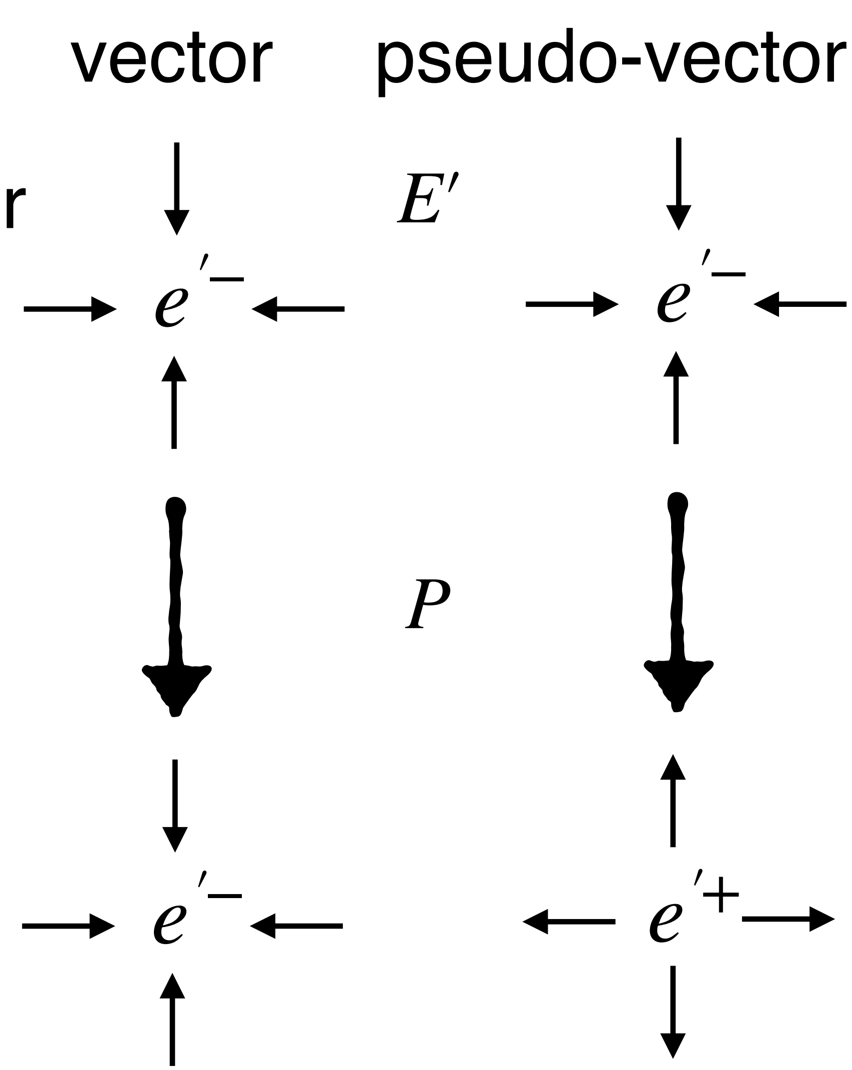
- usually $F'_{\mu\nu}$ tensor and thus $\tilde{F}'_{\mu\nu}$ pseudo-tensor
$\leftrightarrow$ the odd intrinsic parity of dark photon

- the opposite is possible:
E' is pseudo-vector and B' is vector

$$E'^i = -F'^{0i} \qquad B'^i = -\frac{1}{2}\epsilon^{ijk}F'^{jk}$$

- $C(\pi' \to \pi'^T)$ and $P(\pi' \to -\pi'^T)$

- $\epsilon e j^\mu_e \tilde{A}'_\mu$



Semi-annihilation

Coupling to photon with $\frac{\epsilon_Y}{2} Y^{\mu\nu} \tilde{F}'_{\mu\nu}$

- $\frac{(4\pi)^2}{\Lambda^3} \tilde{F}'^{\mu\nu} \mathrm{Tr}[\pi' \partial_\mu \pi' \partial_\nu \pi'] \rightarrow \epsilon c_\epsilon \frac{(4\pi)^2}{\Lambda^3} B^{\mu\nu} \mathrm{Tr}[\pi' \partial_\mu \pi' \partial_\nu \pi']$

  - preserving $C(\pi' \rightarrow \pi'^T)$and $P(\pi' \rightarrow -\pi'^T)$

  - semi-annihilation $\pi'\pi' \rightarrow \pi' A$

- if Bianchi identify $\partial_\mu F'^{\mu\nu} = 0$ holds, on-shell photon cannot be emitted through kinetic mixing

  - $\tilde{F}'_{\mu\nu} = \partial_\mu \tilde{A}'_\nu - \partial_\nu \tilde{A}'_\mu$ and $\partial_\mu B^{\mu\nu} = 0$ by integration by part

- Bianchi identify does not hold $\partial_\mu F'^{\mu\nu} = -e_D j^\nu_{e'}$

Semi-annihilation cross section

$\langle \sigma_{\mathrm{semi}} v \rangle = c_\epsilon^2 \epsilon^2 \frac{4\pi^4 m_{\pi'}^4}{\Lambda^6} \left(\frac{T}{m_{\pi'}} \right)$ - p-wave due to $SU(N_F)$ flavor symmetry

Co-evolution

Which temperature?

- no π'-π'-A interaction → kinetic equilibrium does not hold

$$\langle \sigma_{\rm semi} v \rangle = c_\epsilon^2 \epsilon^2 \frac{4\pi^4 m_{\pi'}^4}{\Lambda^6} \left(\frac{T_{\pi'}}{m_{\pi'}} \right) \qquad T_{\pi'} \neq T$$

- co-evolution of $n_{\pi'}$ and $T_{\pi'}$ through $\pi'\pi' \to \pi' A$
- efficient self-scattering → $f_{\pi'} = \dfrac{n_{\pi'}}{n_{\pi'}^{\rm eq}(T_{\pi'})} e^{-E_{\pi'}/T_{\pi'}}$

Binder, Bringmann, Gustafsson, and Hryczuk, PRD, 2017

- Higgs portal

AK, Kim, Kim, and Sekiguchi, PRL, 2018

- s-wave semi-annihilation

Co-evolution equations

$$\dot{n}_{\pi'} + 3H n_{\pi'} = - n_{\pi'} \langle \sigma_{\rm semi} v \rangle_{T_{\pi'} T_{\pi'}} \left[n_{\pi'} - \mathcal{J}(T_{\pi'}, T) n_{\pi'}^{\rm eq}(T_{\pi'}) \right]$$

$$\dot{T}_{\pi'} + 3H T_{\pi'} \left(\frac{T_{\pi'}}{\sigma_E} \right)^2 = - \left(\frac{T_{\pi'}}{\sigma_E} \right)^2 \frac{n_A^{\rm eq}(T_{\pi'})}{n_{\pi'}^{\rm eq}(T_{\pi'})} \langle \Delta E \sigma_{\rm inv} v \rangle_{T_{\pi'}, T = T_{\pi'}} \left[n_{\pi'} - n_{\pi'}^{\rm eq}(T_{\pi'}) \mathcal{K}(T_{\pi'}, T) \right]$$

- adiabatic cooling
- heating through semi-annihilation

Self-heating

Co-evolution equations simplified $T < T_{\rm fo} \sim m_{\pi'}/20$

- well non-relativistic and negligible inverse process

$$\frac{d}{dx}Y_{\pi'} \approx -\frac{\lambda}{x^2}Y_{\pi'}^2 \qquad Y_{\pi'} = \frac{n_{\pi'}}{s} \quad x_{\pi'} = \frac{m_{\pi'}}{T_{\pi'}} \quad x = \frac{m_{\pi'}}{T}$$

$$x\frac{d}{dx}\left(\frac{x_{\pi'}}{x}\right) \approx \frac{x_{\pi'}}{x} + \frac{2}{3}\bar{\lambda}Y_{\pi'}\left(\frac{x_{\pi'}}{x}\right)^2 \qquad \lambda = \frac{xs\langle\sigma_{\rm semi}v\rangle}{2H} \qquad \bar{\lambda} = -\left(\frac{5}{4}-1\right)\lambda$$

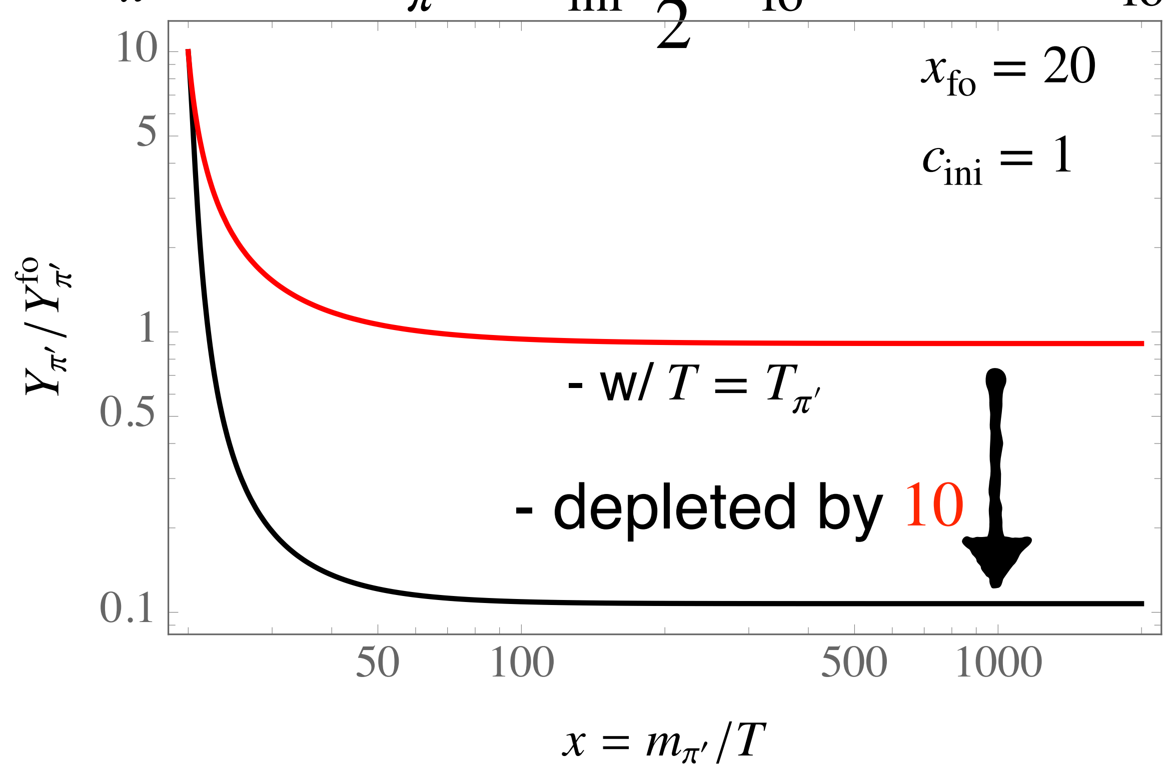
- one particle depleted per semi-annihilation

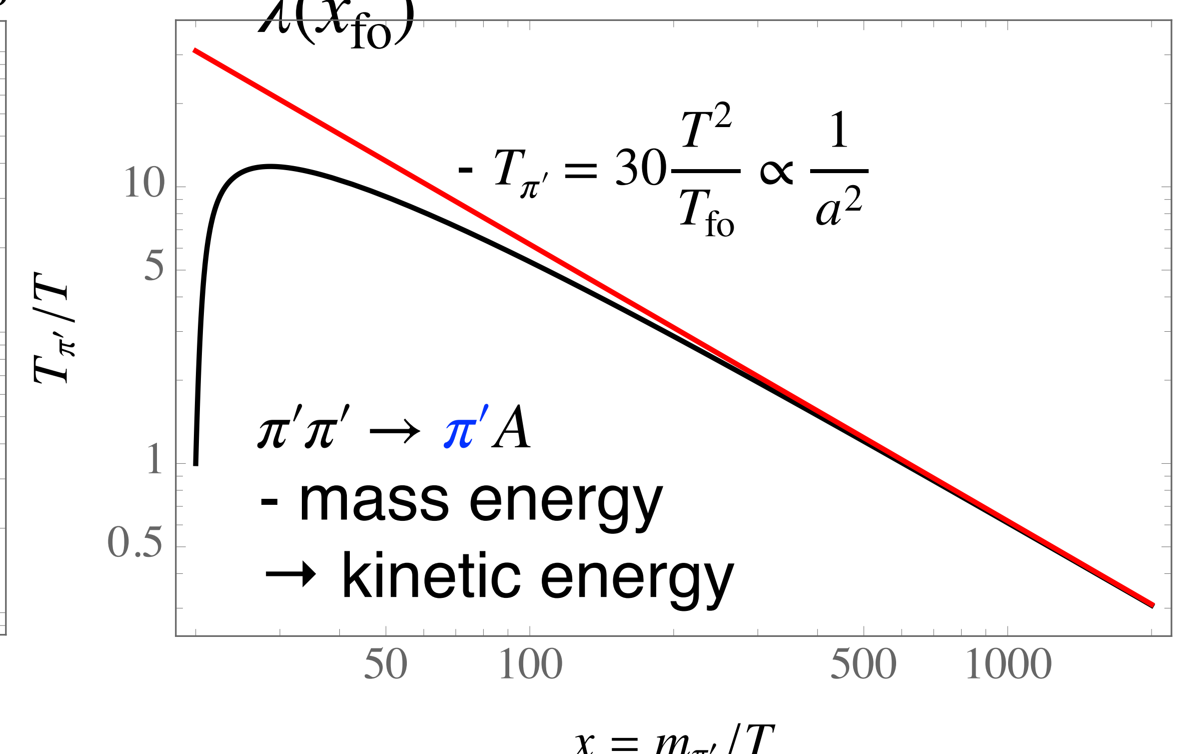
- energy of $\pi'\pi' \to \pi' A$

- initial condition

$$x_{\pi'} = x \quad Y_{\pi'} = c_{\rm ini}\frac{x_{\rm fo}}{2}Y_{\rm fo} \text{ at } x = x_{\rm fo} \qquad Y_{\rm fo} = \frac{2x_{\rm fo}}{\lambda(x_{\rm fo})}$$

- p-wave





Parameter plot

AK, Kim, Kim, and Sekiguchi, PRL, 2018

p -wave self-heating

- $Y_{\pi'}^{\infty} \sim 0.1 \times Y_{\rm fo}$ $\quad T_{\pi'} \sim 30\dfrac{T^2}{T_{\rm fo}} \propto \dfrac{1}{a^2}$
- 5 times smaller cross section $\langle \sigma_{\rm semi} v \rangle \simeq 6 \times 10^{26}\,{\rm cm}^3/{\rm s}$

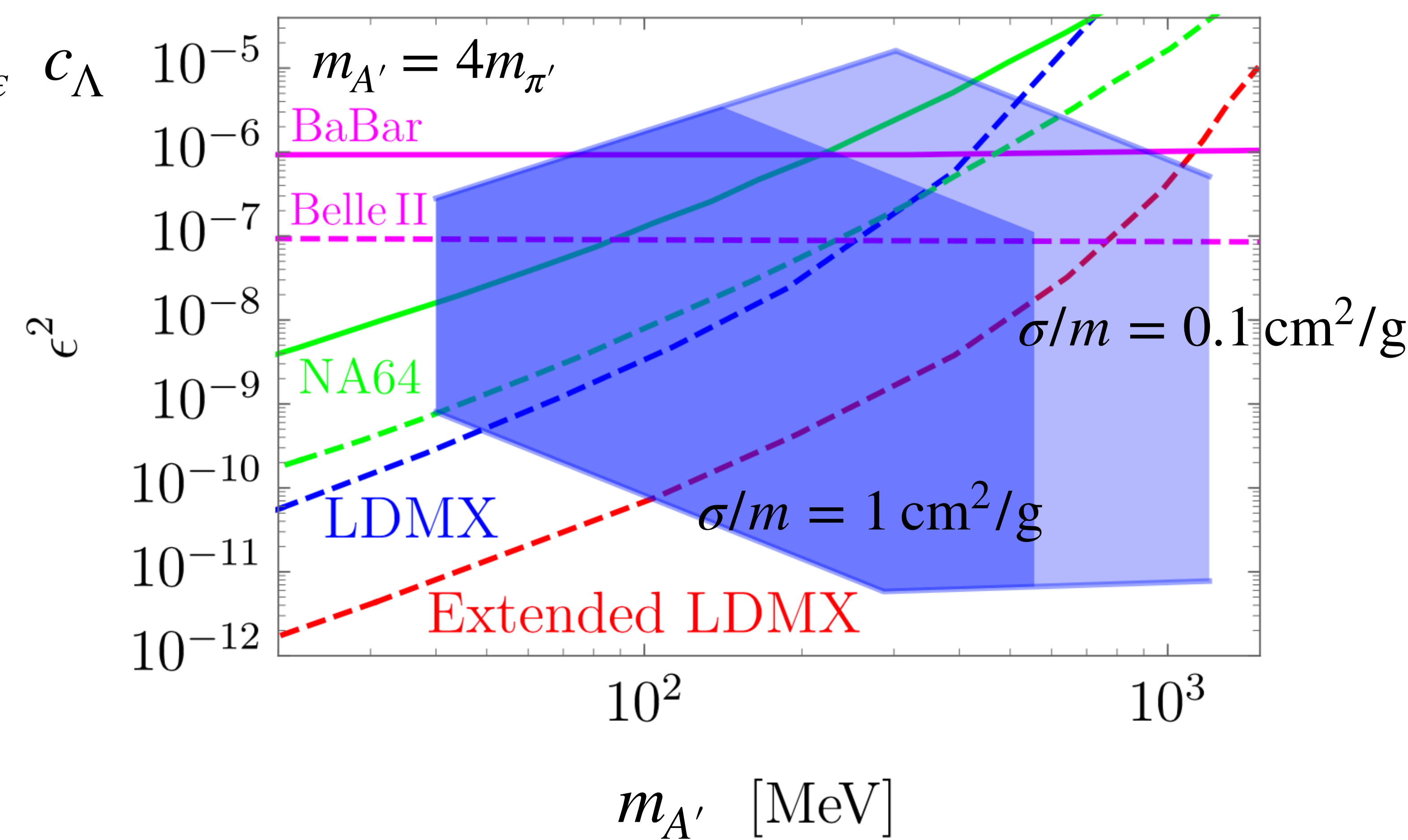
$$\epsilon = 2 \times 10^{-7} c_{\epsilon}^{-1} c_{\Lambda}^{-3} \left(\frac{m_{\pi'}}{100\,{\rm MeV}} \right)$$

- $x_{\rm fo}$ $c_{\rm ini}$ ← full co-evolution equations (future work)
- absorb uncertainties in c_{ϵ} c_{Λ}

$c \in (0.1, 1)$ $\quad c_1 c_{\Lambda}^2 < 1/(4\pi)$

s -wave self-heating

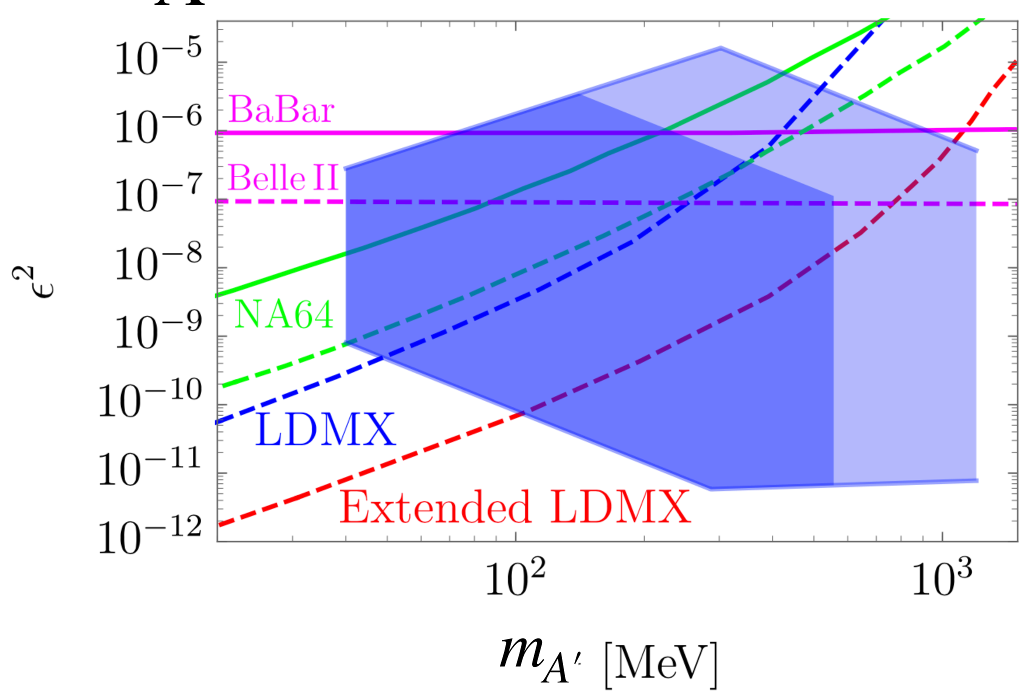
- tiny change in Y_{χ}
- $T_{\chi} = 5 \times T \propto \dfrac{1}{a}$



Kinetic mixing

$$\frac{\epsilon'_Y}{2} Y^{\mu\nu} F'_{\mu\nu} = -\frac{\epsilon'_Y}{2} \tilde{Y}^{\mu\nu} \tilde{F}'_{\mu\nu}$$

- E' is vector and B' is pseudo-vector as usual
- $-\epsilon e j^{\mu}_{\rm m} A'_{\mu}$, but no $\epsilon e j^{\mu}_{\rm e} A'_{\mu}$
- No dark photon production, but DM production through virtual photon
- $\frac{(4\pi)^2}{\Lambda^3} \tilde{F}'^{\mu\nu} \mathrm{Tr}[\pi' \partial_\mu \pi' \partial_\nu \pi'] \rightarrow \epsilon c_\epsilon \frac{(4\pi)^2}{\Lambda^3} \tilde{B}^{\mu\nu} \mathrm{Tr}[\pi' \partial_\mu \pi' \partial_\nu \pi']$



- preserving $C(\pi' \rightarrow \pi'^T)$ and $P(\pi' \rightarrow -\pi')$
- semi-annihilation $\pi'\pi' \rightarrow \pi' A$
- DM production

- LDMX sensitivity changes slightly $\epsilon \rightarrow \epsilon'$ $m_{A'} \rightarrow \Lambda$

Kinetic mixing

$$\frac{\epsilon_Y}{2} Y^{\mu\nu} \tilde{F}'_{\mu\nu} + \frac{\epsilon'_Y}{2} Y^{\mu\nu} F'_{\mu\nu}$$

	Q_e	Q_m	Q_{eD}	Q_{mD}	
electron	-1	0	0	$-\epsilon$	
monopole	0	-1	0	$-\epsilon'$	
"electron"	ϵ'	$-\epsilon$	-1	0	- dyon - violating P
"monopole"	0	0	0	-1	- condensation

Dirac quantization for dyons **Schwinger, Science, 1969**

$$(Q_e Q'_m - Q'_e Q_m) + (Q_{eD} Q'_{mD} - Q'_{eD} Q_{mD}) = 1$$

Summary

SIMP DM motivated by small-scale issues (cosmic frontier)

Dark photon portal to light DM under extensive search (intensity frontier)

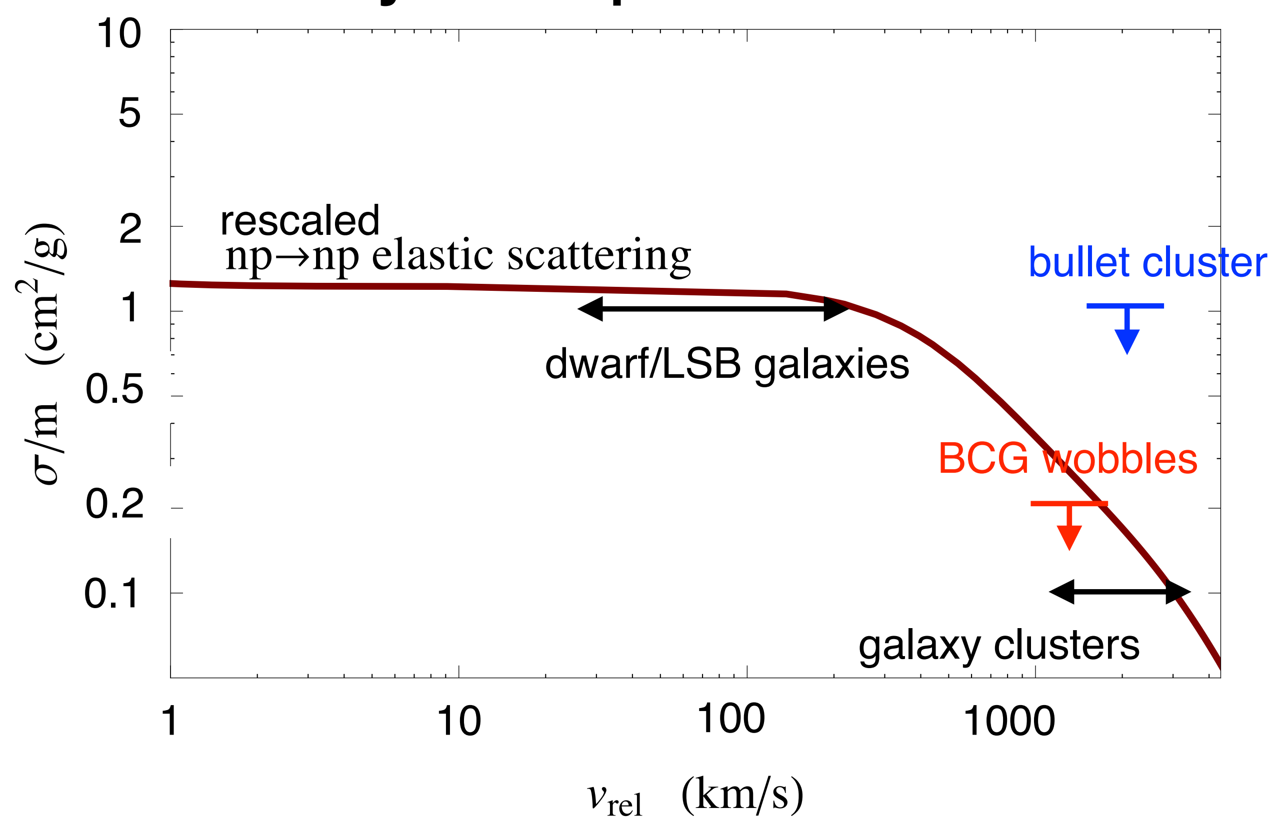
Integrate SIMP and dark photon in light “electron”-“monopole” theory

“electron”-“positron” as SIMP DM only detectable in LDMX-type experiments (not in beam-dump experiments)

p-wave semi-annihilation into photon → self-heating

Discussion

SIMP DM → velocity-independent cross section



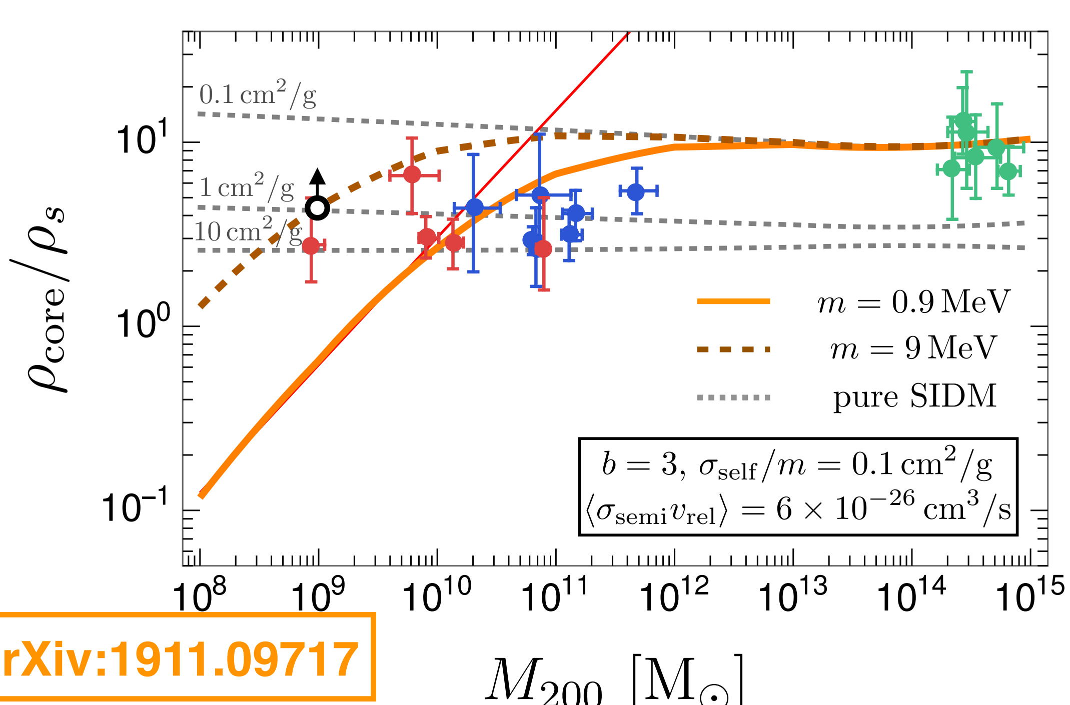
Randall *et al.*, ApJ, 2008

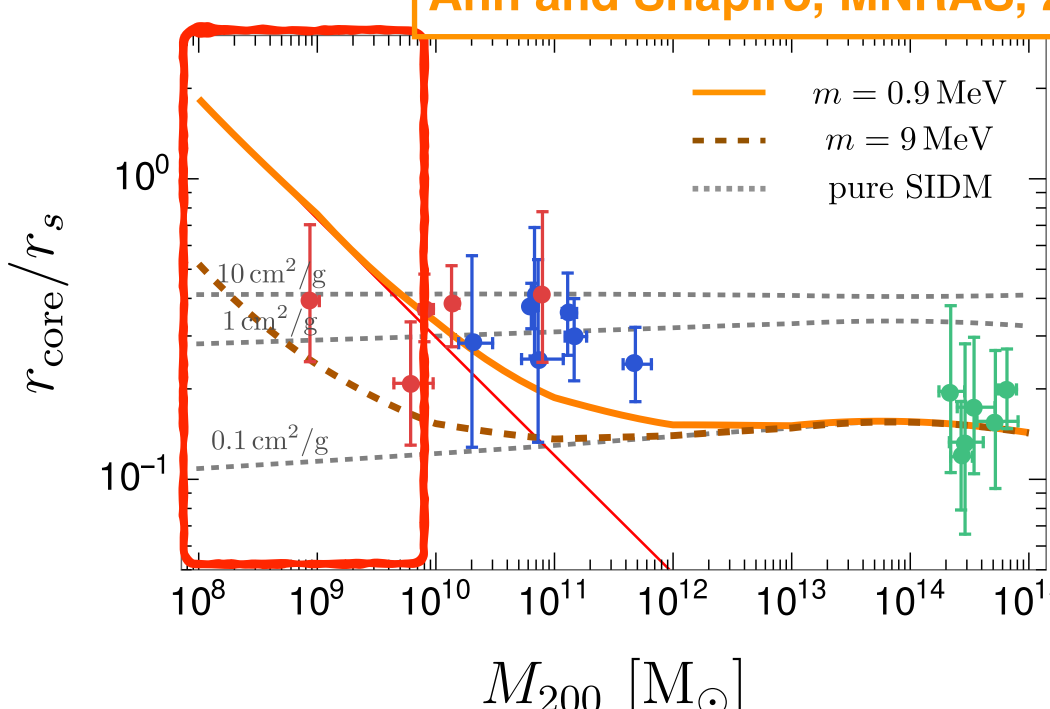
Harvey, Robertson, Massay, and McCarthy, MNRAS, 2019

Kaplinghat, Tulin, and Yu, PRL, 2016

Self-heating in a halo → different from SIDM (“duality") $r_{\rm core} \lesssim 0.5 r_s$

Ann and Shapiro, MNRAS, 2005





AK and Kim, arXiv:1911.09717

Cosmic frontier

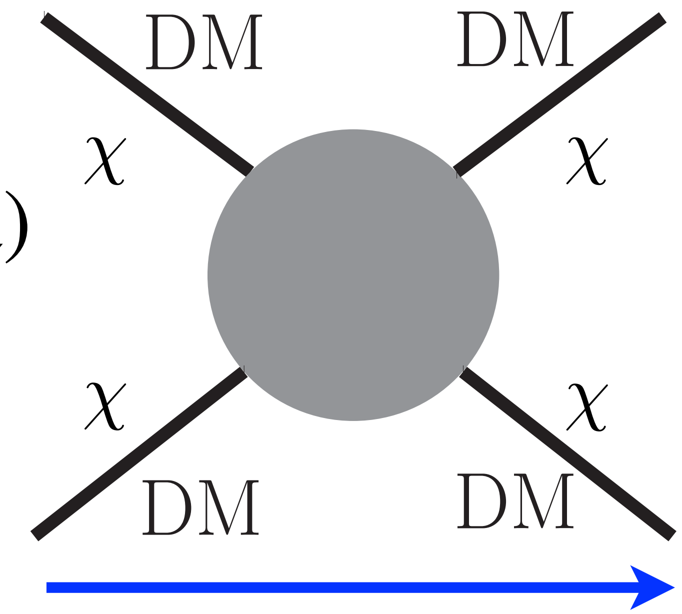
Thank you for your attention

Co-evolution equations

AK, Kim, Kim, and Sekiguchi, PRL, 2018

Efficient self-scattering

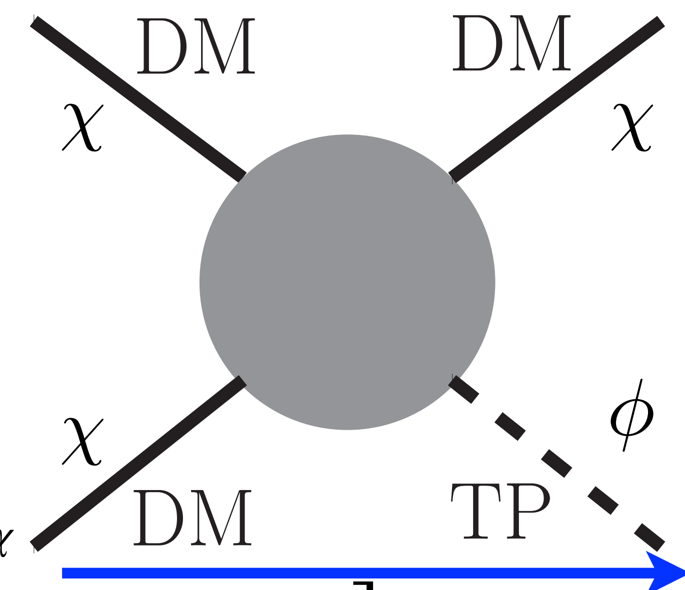
$$\rightarrow \quad f_\chi = \frac{n_\chi}{n_\chi^{\rm eq}(T_\chi)} \exp(-E_\chi/T_\chi)$$



$T_\chi = T_\phi$

→ Boltzmann equation for WIMP freeze-out

Co-evolution equations



$$\dot{n}_\chi + 3Hn_\chi = -\, n_\chi \langle \sigma_{\rm semi} v \rangle_{T_\chi T_\chi} \left[n_\chi - \mathscr{J}(T_\chi, T_\phi) n_\chi^{\rm eq}(T_\chi) \right]$$

$$\dot{T}_\chi + 3HT_\chi \left(\frac{T_\chi}{\sigma_E} \right)^2 = -\left(\frac{T_\chi}{\sigma_E} \right)^2 \frac{n_\phi^{\rm eq}(T_\chi)}{n_\chi^{\rm eq}(T_\chi)} \langle \Delta E \sigma_{\rm inv} v \rangle_{T_\chi, T_\phi = T_\chi} \times \left[n_\chi - n_\chi^{\rm eq}(T_\chi) \mathscr{K}(T_\chi, T_\phi) \right]$$

- adiabatic cooling

- heating through semi-annihilation

relativistic: $\sigma_E^2 = 3T_\chi \quad \rightarrow \quad T_\chi \propto 1/a$

non-relativistic: $\sigma_E^2 = 3/2T_\chi \rightarrow T_\chi \propto 1/a^2$

Co-evolution equations

$$\dot{n}_\chi + 3Hn_\chi = -n_\chi \langle \sigma_{\rm semi} v \rangle_{T_\chi T_\chi} \Big[n_\chi - \mathscr{J}(T_\chi, T_\phi) n_\chi^{\rm eq}(T_\chi) \Big]$$

$$\dot{T}_\chi + 3HT_\chi \left(\frac{T_\chi}{\sigma_E} \right)^2 = -\left(\frac{T_\chi}{\sigma_E} \right)^2 \frac{n_\phi^{\rm eq}(T_\chi)}{n_\chi^{\rm eq}(T_\chi)} \langle \Delta E \sigma_{\rm inv} v \rangle_{T_\chi, T_\phi = T_\chi} \times \Big[n_\chi - n_\chi^{\rm eq}(T_\chi) \mathscr{K}(T_\chi, T_\phi) \Big]$$

$$\sigma_E^2 = \langle E_\chi^2 \rangle - \langle E_\chi \rangle^2$$

$$\mathscr{J}(T_\chi, T_\phi) = \frac{n_\phi^{\rm eq}(T_\phi)}{n_\phi^{\rm eq}(T_\chi)} \frac{\langle \sigma_{\rm inv} v \rangle_{T_\chi, T_\phi}}{\langle \sigma_{\rm inv} v \rangle_{T_\chi, T_\phi = T_\chi}}$$

$$\mathscr{K}(T_\chi, T_\phi) = \frac{n_\phi^{\rm eq}(T_\phi)}{n_\phi^{\rm eq}(T_\chi)} \frac{\langle \Delta E \sigma_{\rm inv} v \rangle_{T_\chi, T_\phi}}{\langle \Delta E \sigma_{\rm inv} v \rangle_{T_\chi, T_\phi = T_\chi}}$$

$$\Delta E = E_\phi - \langle E_\chi \rangle_{T_\chi}$$

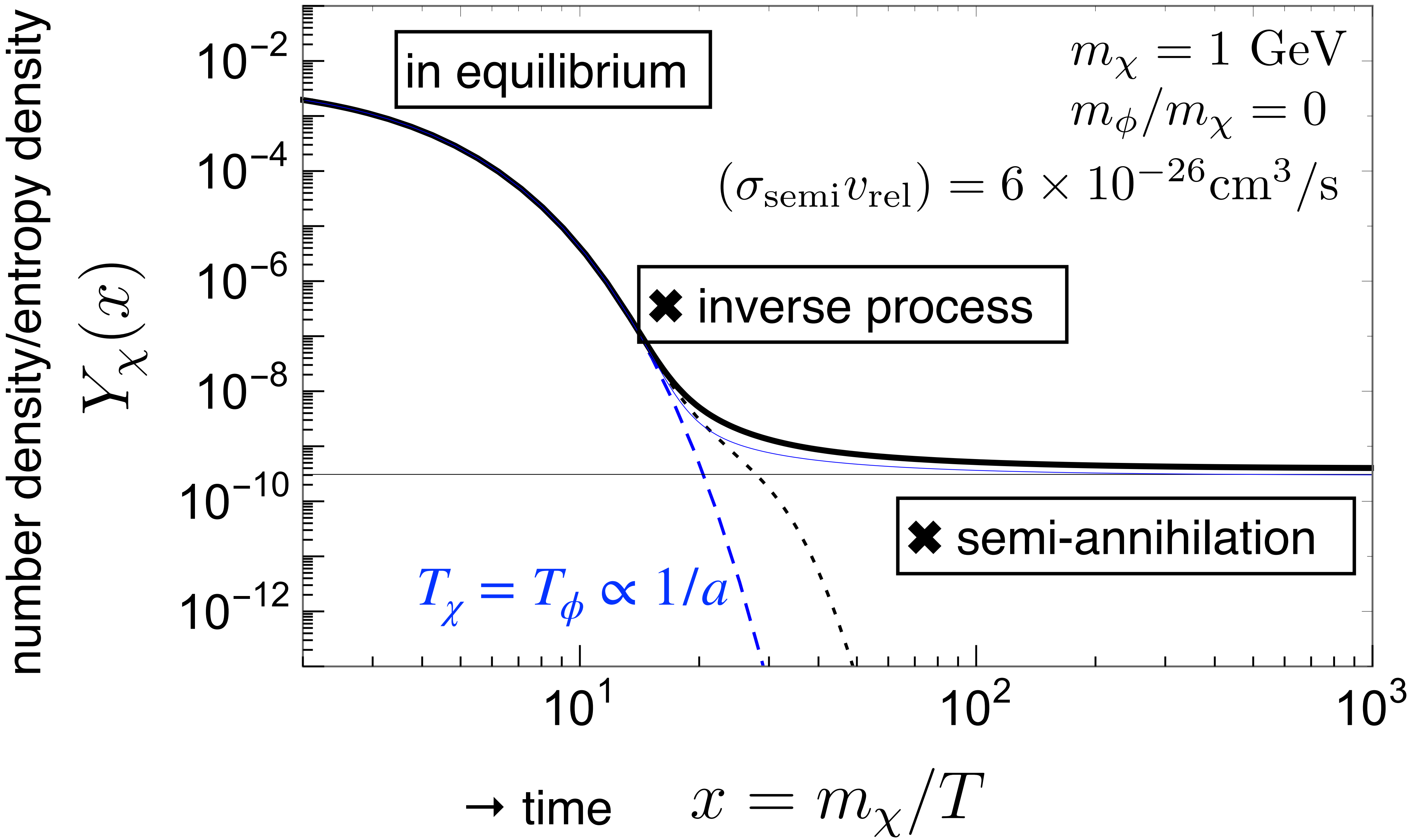
relativistic: $\sigma_E^2 = 3T_\chi$

non-relativistic: $\sigma_E^2 = 3/2 T_\chi$

$$\mathscr{J}(T_\chi = T_\phi, T_\phi) = 1$$

$$\mathscr{K}(T_\chi = T_\phi, T_\phi) = 1$$

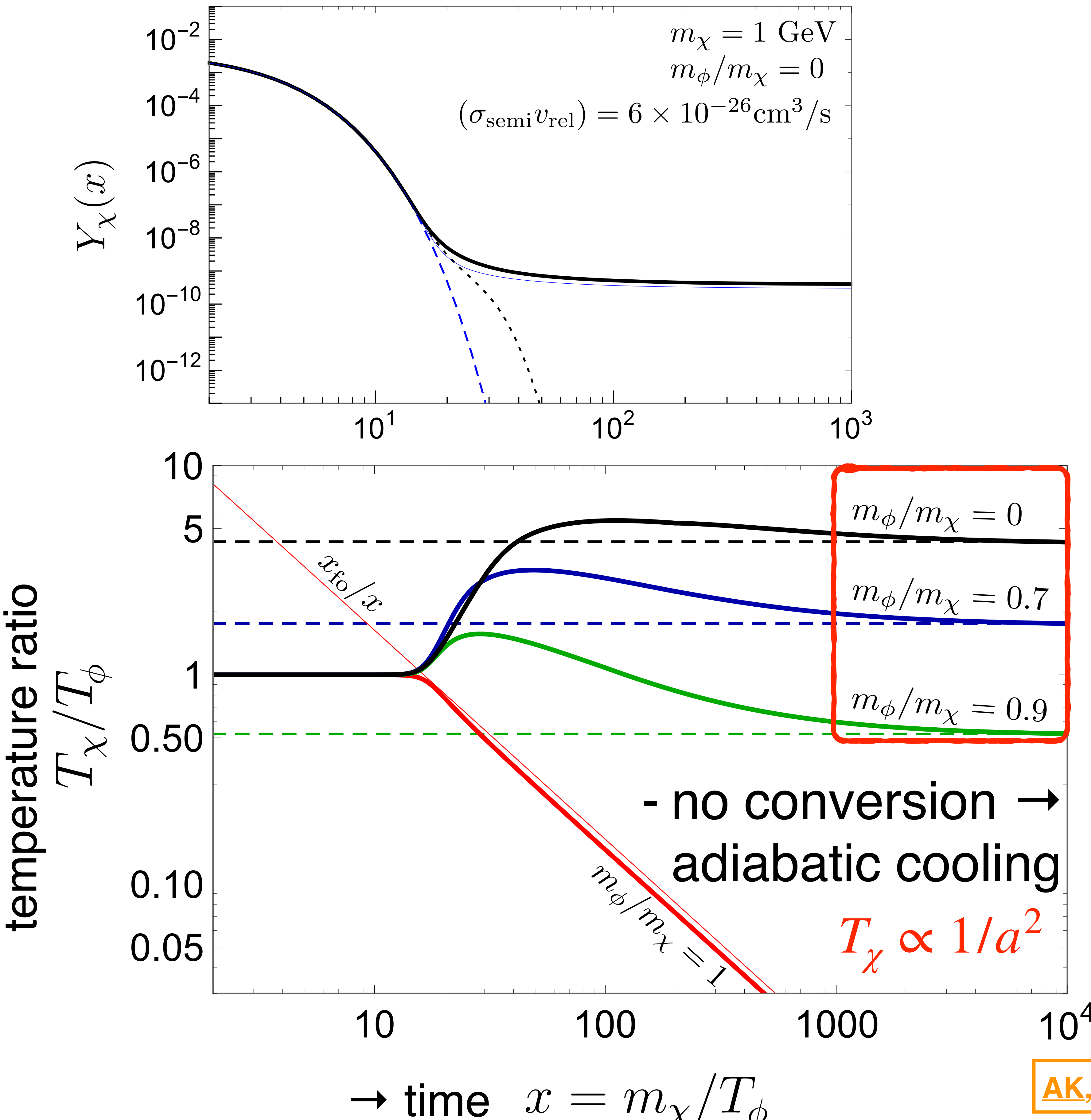
Freeze-out



Proceed as WIMP freeze out

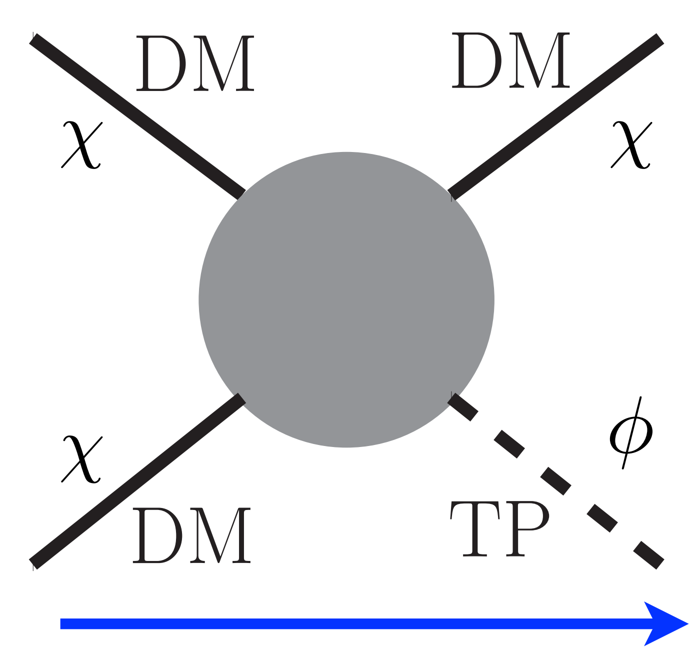
- $30\,\%$ difference in the relic abundance compared to $T_\chi = T_\phi \propto 1/a$

Freeze-out



- mass deficit converted into the kinetic energy

→ self-heating $T_\chi \propto 1/a$



AK, Kim, Kim, and Sekiguchi, PRL, 2018

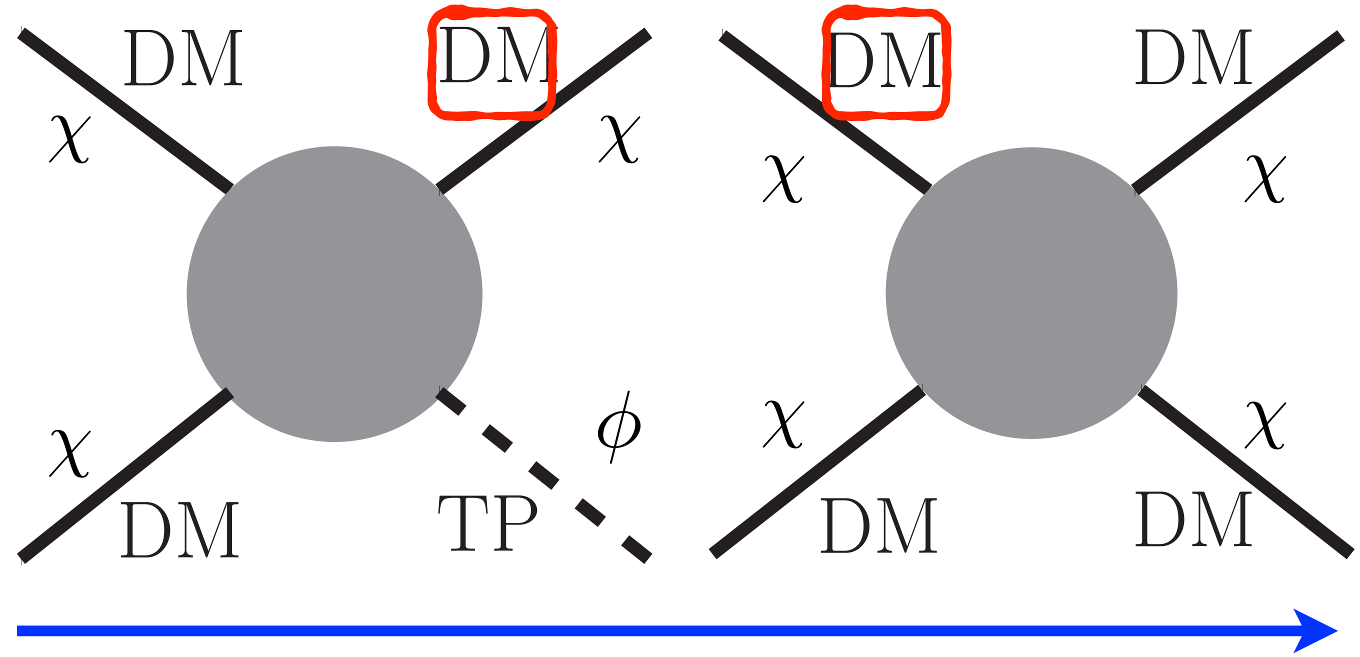
Post-freeze-out evolution

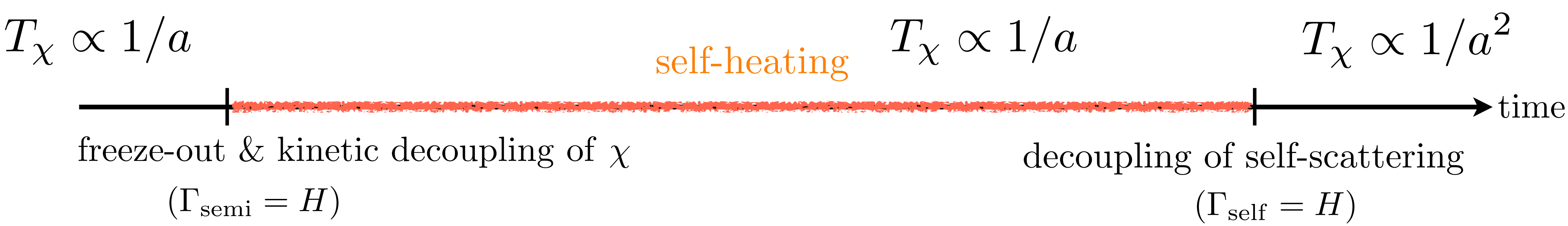
Semi-annihilation

- only a tiny part of DM

Self-scattering

- sharing the mass deficit w/ others $m \gg T$

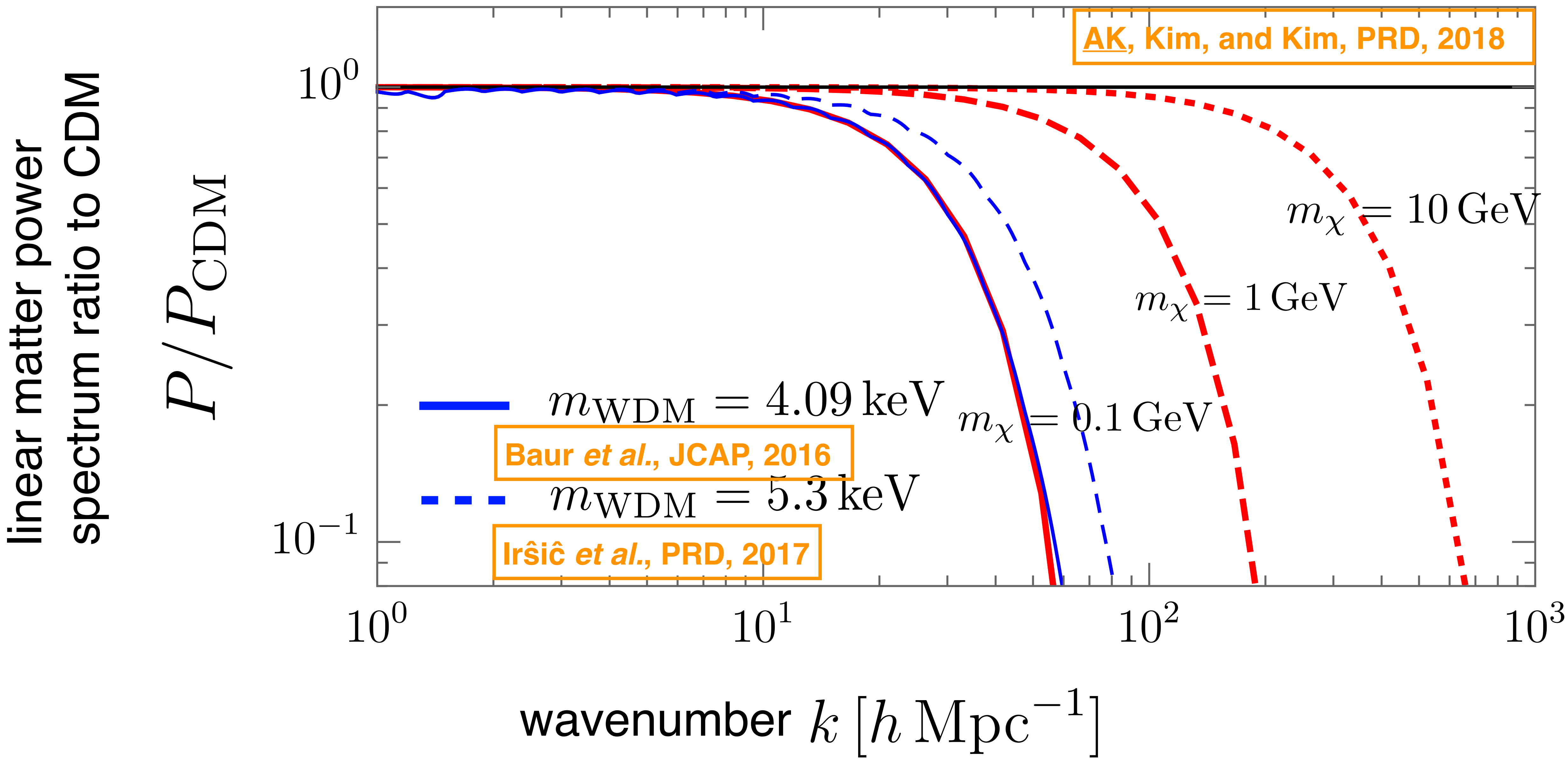




Decoupling of self-scattering (radiation-dominated)

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

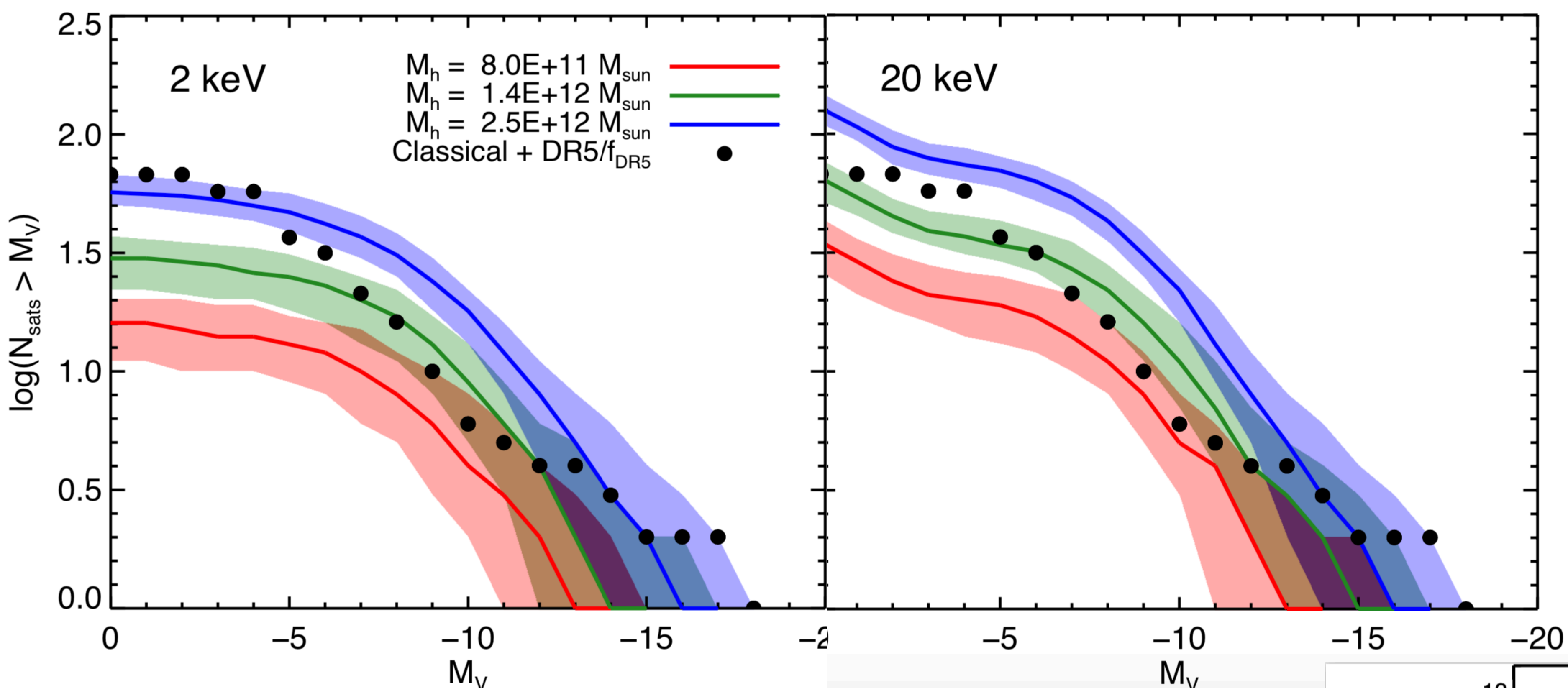
Suppression of Galactic-scale structure



Sub-GeV SHDM behaves as warm dark matter (WDM)

$$\frac{m_{\rm WDM}}{5.3\,\mathrm{keV}} \simeq \left(\frac{r_{\chi\phi}}{2.4}\right)^{-3/8} \left(\frac{m_\chi}{0.1\,\mathrm{GeV}}\right)^{3/8} \max\left(1, \sqrt{a_{\rm eq}/a_{\rm self}}\right)^{3/4} \left(\frac{T_\gamma}{T_\phi}\right)^{3/8}_{\rm eq}$$

Missing satellite problem w/ WDM



cumulative number of subhalos

luminosity

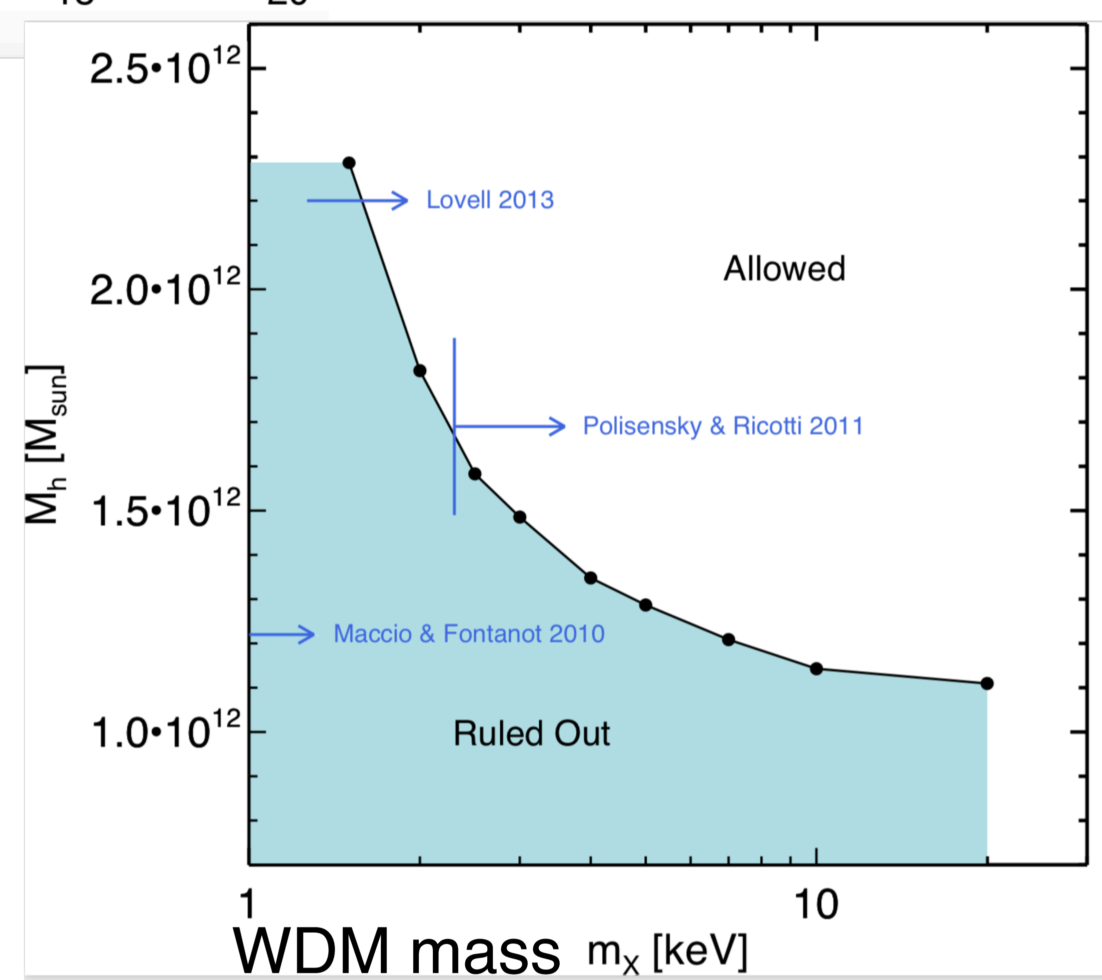
Kennedy, Frenk, Cole, and Benson, MNRAS, 2014

WDM reduces a predicted number of satellite galaxies

Should not go below the observed number

$\rightarrow m_{\rm WDM} \gtrsim 2\,{\rm keV}$

MW halo mass

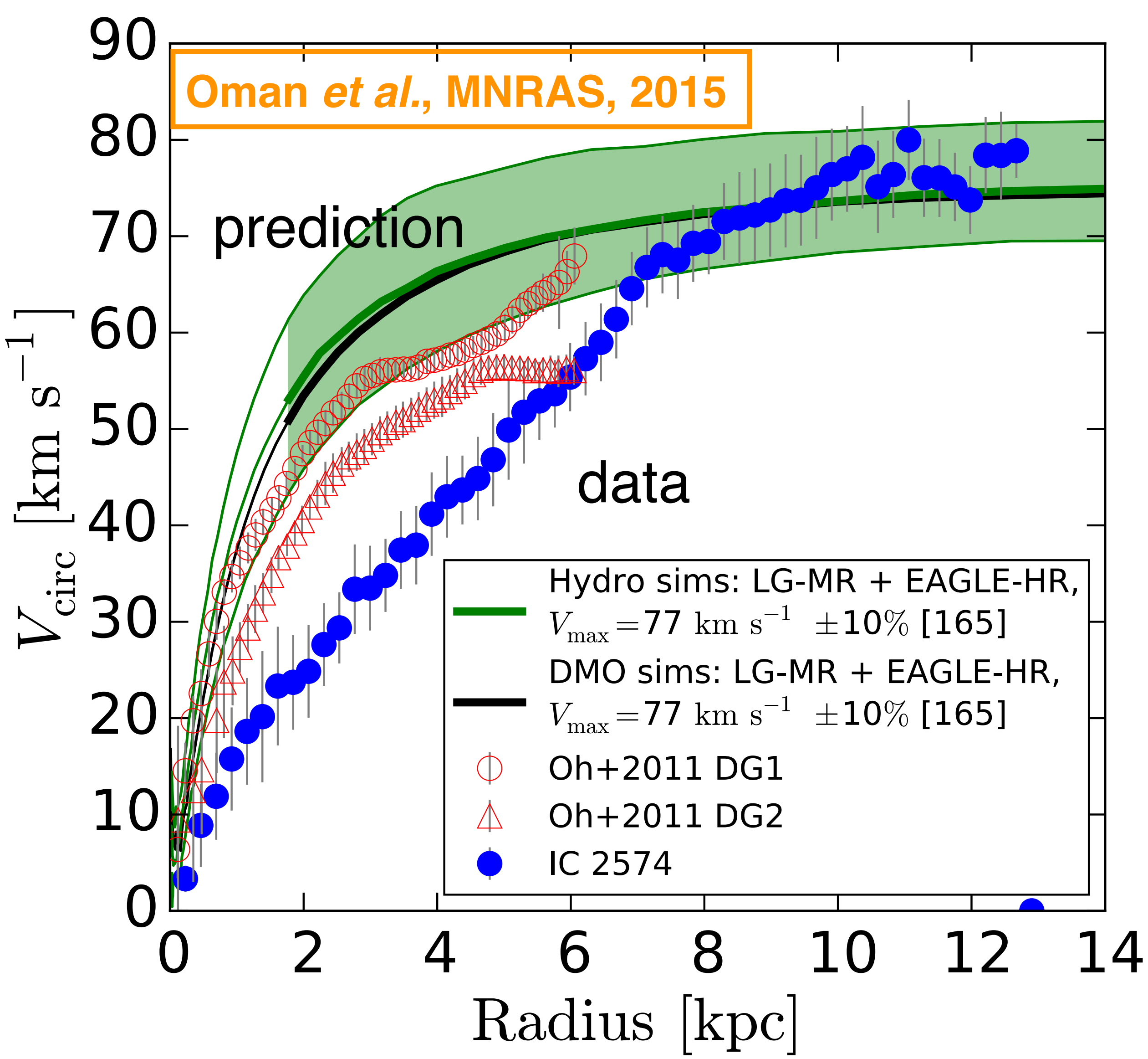


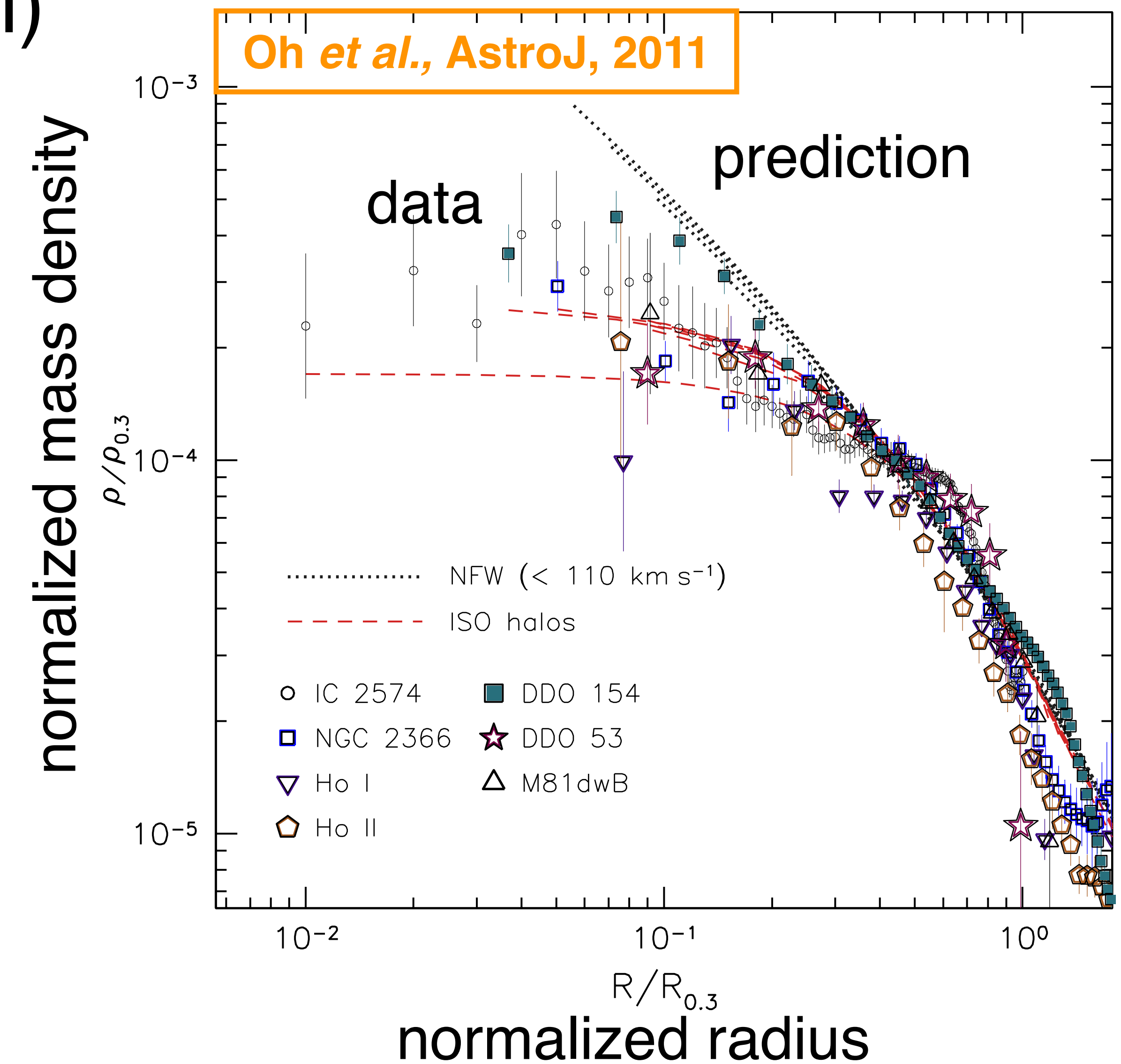
WDM mass

Core-cusp problem

Collisionless cold dark matter (CDM)
→ cuspy profile

Observed dwarf/law-surface brightness (LSB) galaxies
→ cored profile $M \sim 10^{10\text{-}11} M_\odot$





a.k.a. inner mass deficit problem

- overpredict the circular velocity by a factor of ~ 2 (~ 4 in mass)

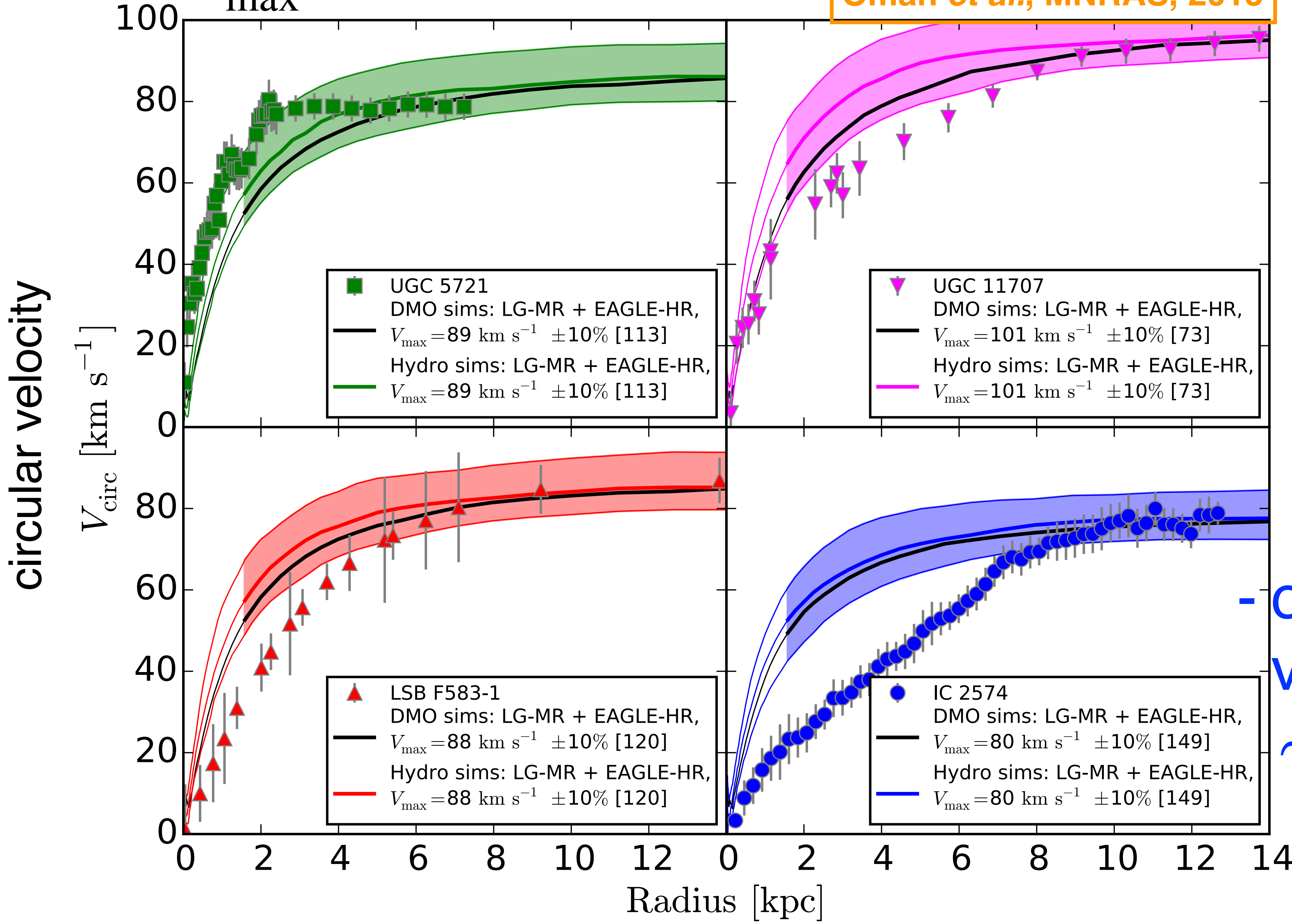
Diversity of inner rotation curves

Collisionless dark matter prediction: inner circular velocity is almost uniquely determined by outer circular velocity

↔ observations show diversity

$V_{max} = 80\text{-}100\,\mathrm{km/s}$

Oman *et al.*, MNRAS, 2015



✴ unique prediction is related with the concentration-mass relation

- overpredict the circular velocity by a factor of ~ 2 (~ 4 in mass)

Key observation

Iso-thermal → Boltzmann distribution

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

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

- inner profile is exponentially sensitive to baryon distribution

Baryons form complex objects, which show a large diversity

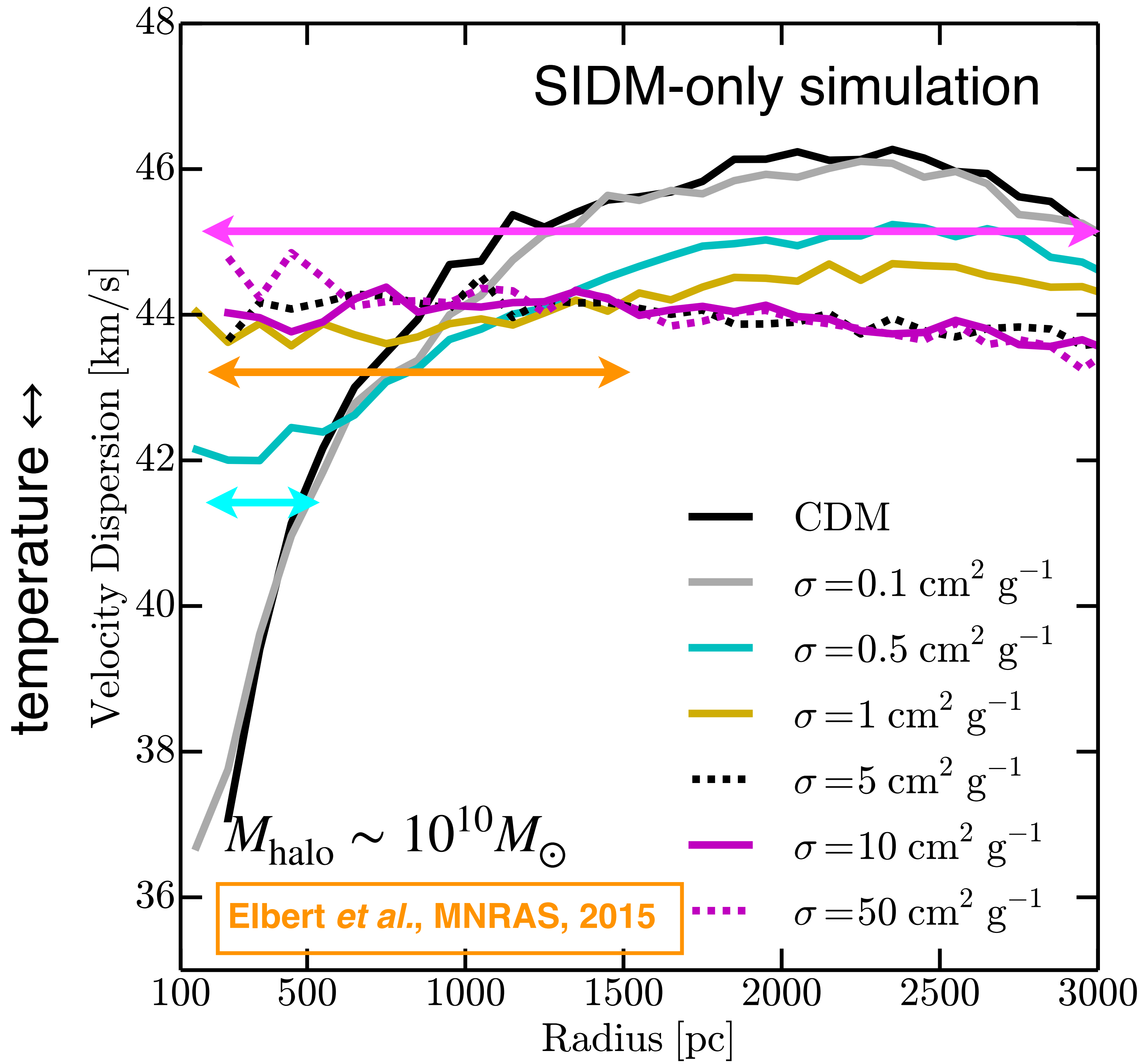
→ SIDM particles, redistributed according to formed baryonic objects, can show a diversity

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

Iso-thermal halo

Self-scattering leads to thermalization of DM halos at $r < r_1$
where self-scattering happens at least one time until now

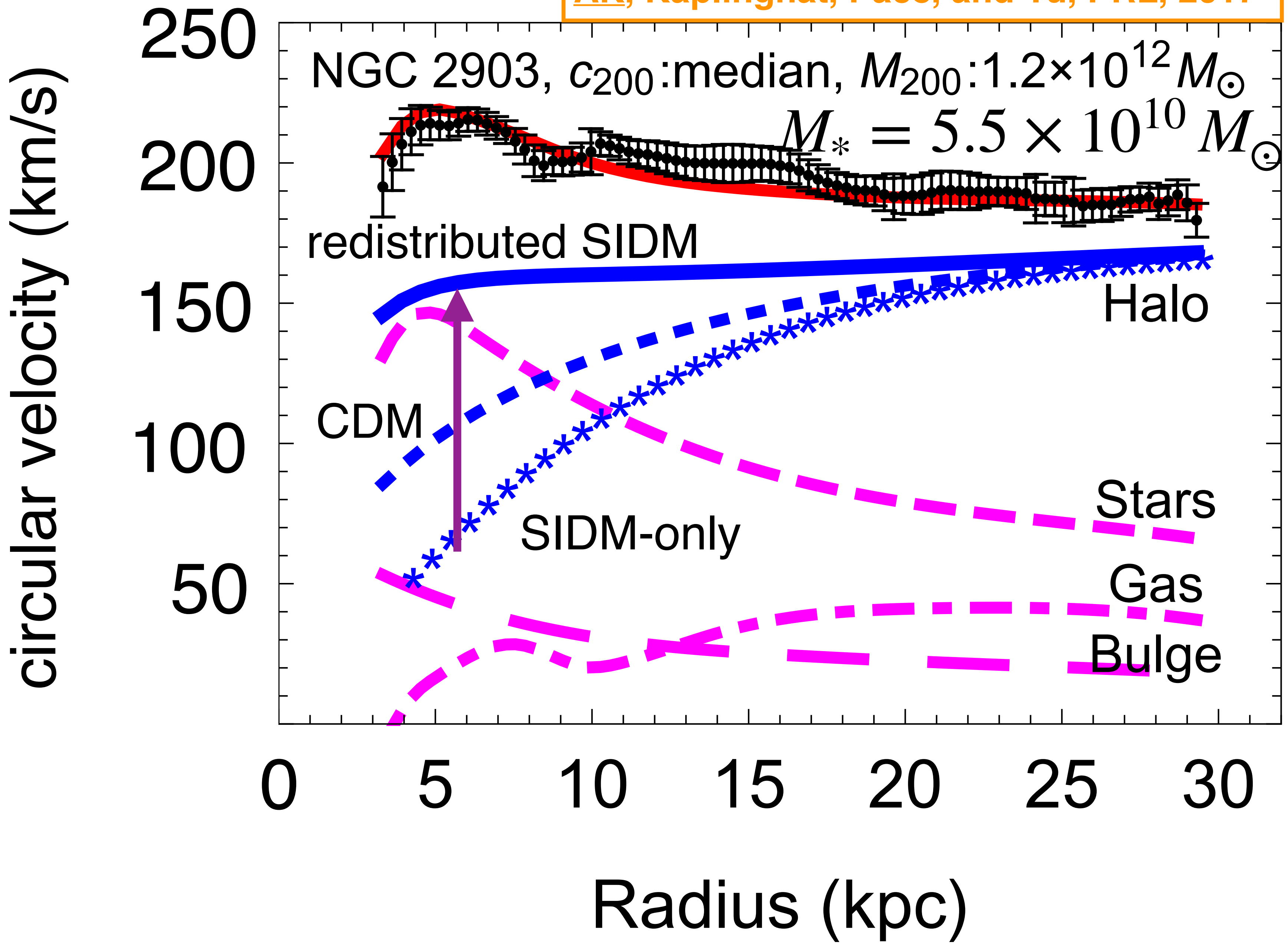
$$\sigma/m\,\rho(r_1)v(r_1)\,t_{\rm age} = 1$$



Impacts in observed galaxies

$\ast$ Hereafter $\sigma/m = 3\,\mathrm{cm^2/g}$

AK, Kaplinghat, Pace, and Yu, PRL, 2017



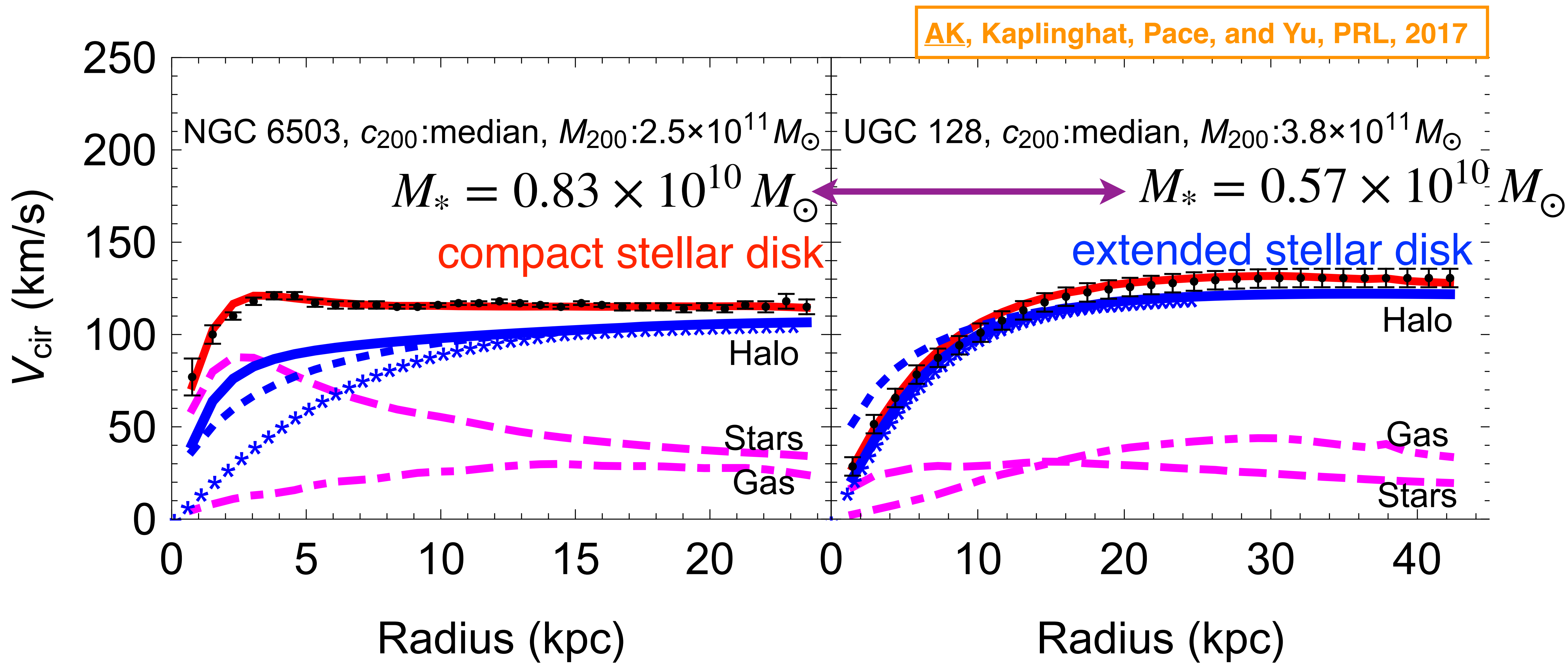
- Observed stellar disk makes SIDM inner circular velocity ~ 3 times higher

→ reproducing flat circular velocity at $10\text{-}20\,\mathrm{kpc}$

Diversity in stellar distribution

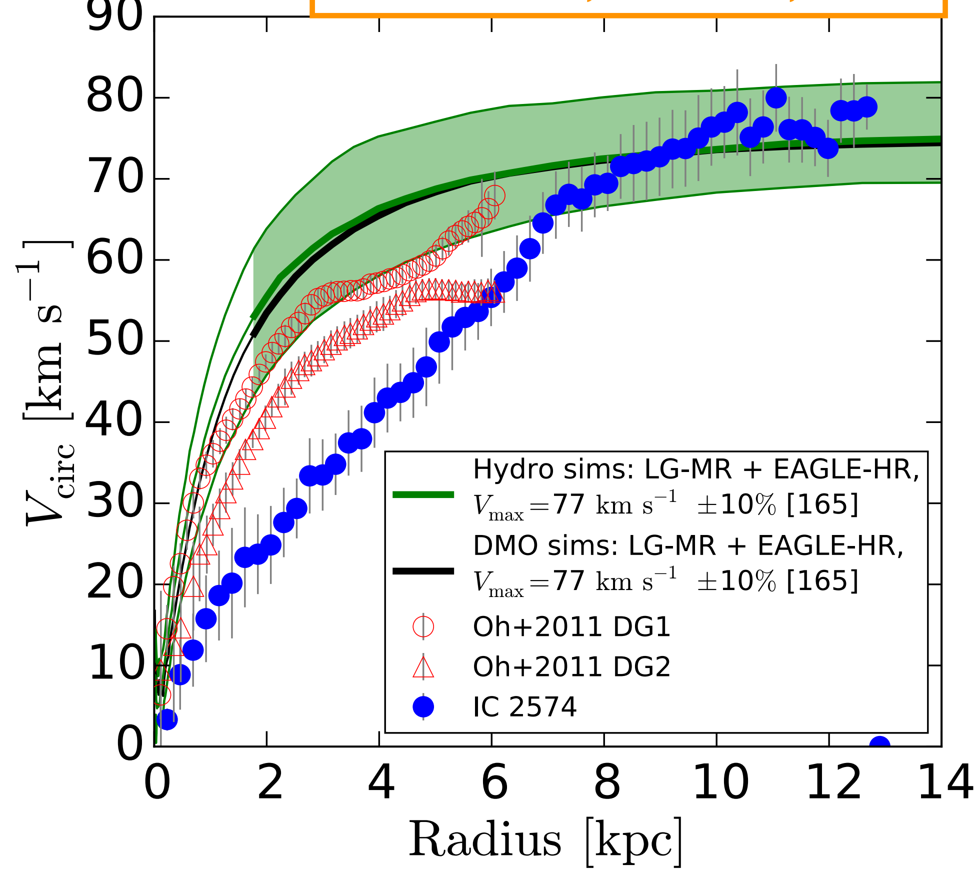
Similar outer circular velocity and stellar mass,
but different stellar distribution

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



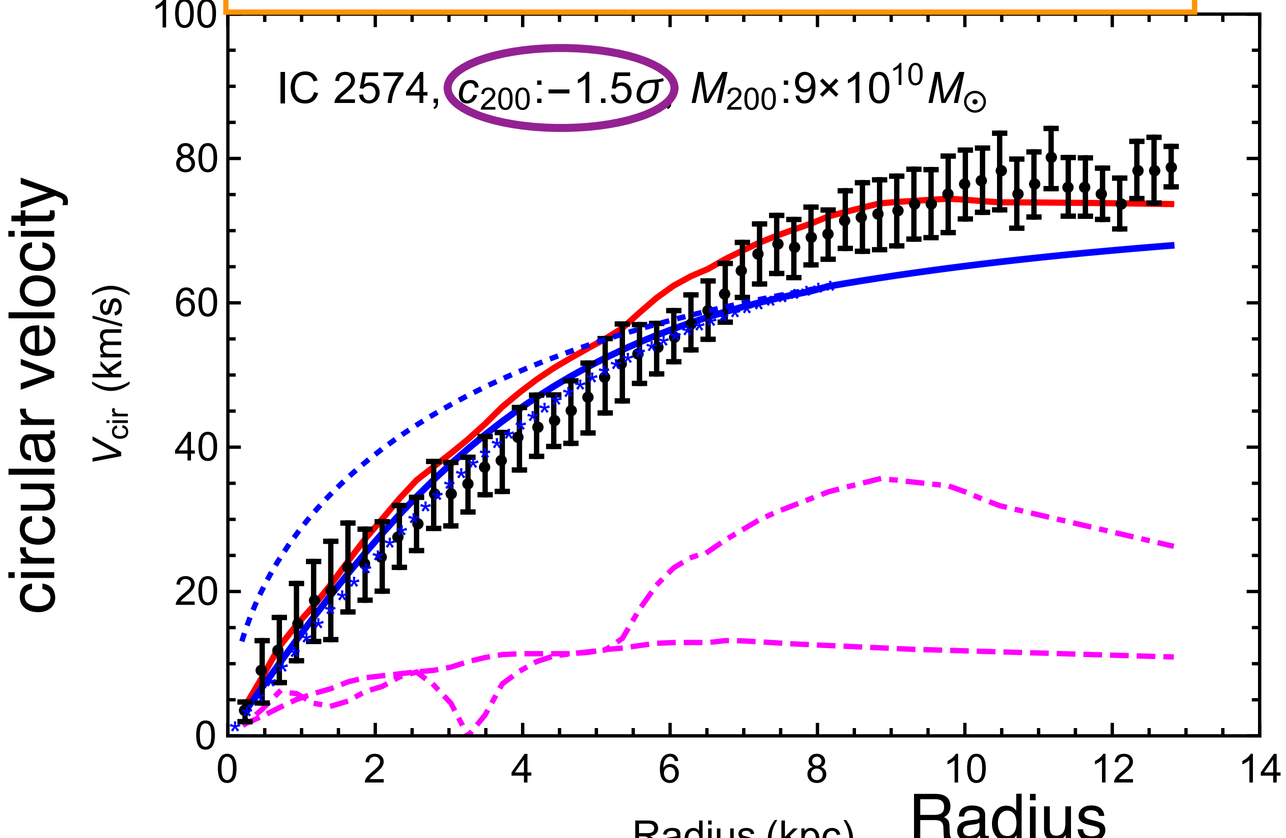
Intrinsic scatter

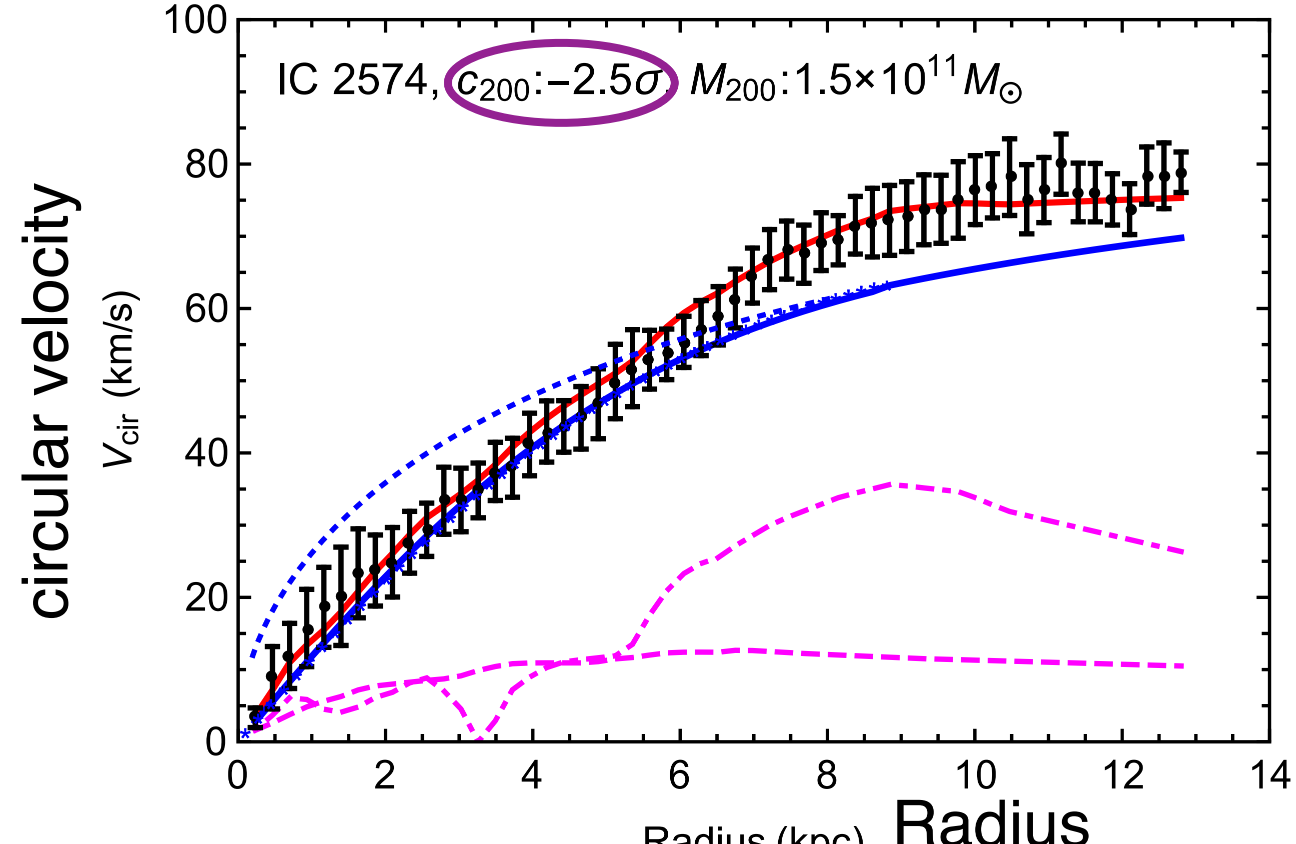
Oman *et al.*, MNRAS, 2015



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

AK, Kaplinghat, Pace, and Yu, PRL, 2017





Gravothermal evolution

DM fluid: Lagrangian picture

$$\frac{\partial M}{\partial r} = 4\pi r^2 \rho$$ - equation of continuity

$$\frac{\partial \left(\rho \nu^2\right)}{\partial r} + \frac{GM\rho}{r^2} = 0$$ - hydrostatic equilibrium

$$\frac{3}{\nu}\left(\frac{\partial \nu}{\partial t}\right)_M - \frac{1}{\rho}\left(\frac{\partial \rho}{\partial t}\right)_M = \frac{1}{\nu^2}\frac{\delta u}{\delta t}$$ - energy conservation

- nature of DM

Initial condition: NFW profile

$$\rho_{\mathrm{NFW}} = \frac{\rho_s}{r/r_s(1 + r/r_s)^2}$$ w/ concentration-mass relation $\leftrightarrow$ ρ_s - r_s

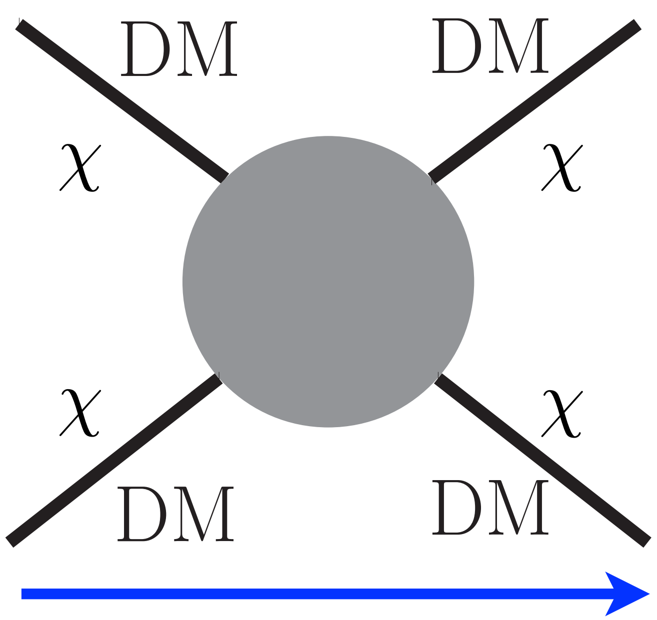
Dutton and Macciò, MNRAS, 2014

Self-scattering

Pure SIDM - heat conduction **Koda and Shapiro, MNRAS, 2011**

$$\lambda = \frac{m}{\sigma_{\rm self}\rho}$$ - free-streaming length

$$H = \sqrt{\frac{\nu^2}{4\pi G\rho}}$$ - Jeans (gravitational) length



$$\frac{\delta u_{\rm cond}}{\delta t} = -\frac{1}{4\pi r^2\rho}\frac{\partial L}{\partial r} \qquad \frac{L}{4\pi r^2} = -\kappa m \frac{\partial}{\partial r}\nu^2 \qquad \kappa^{-1} = \kappa_{\rm SMFP}^{-1} + \kappa_{\rm LMFP}^{-1}$$

- conductivity

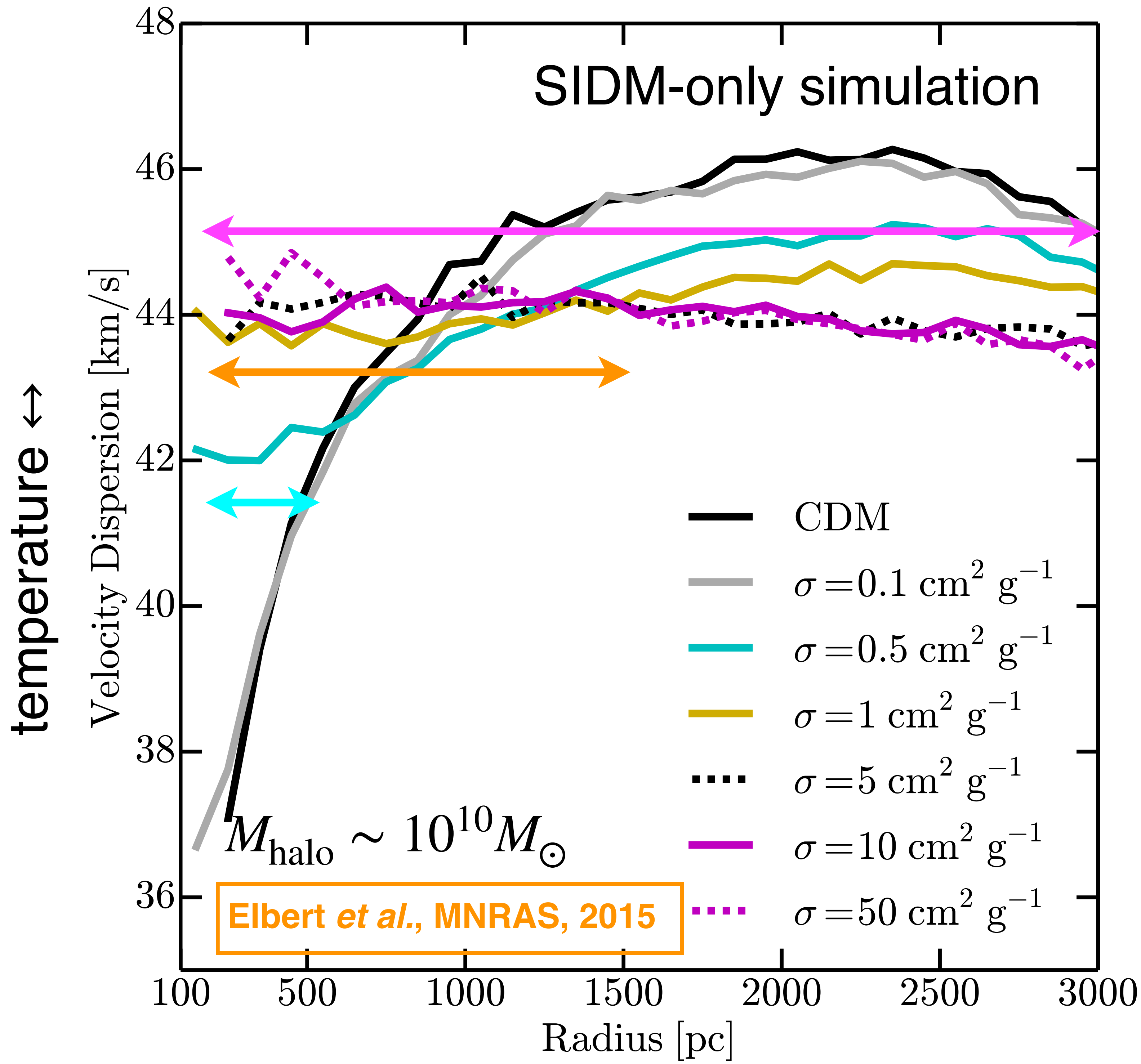
$$\kappa_{\rm SMFP} = \frac{75\sqrt{\pi}}{64}\frac{\rho\lambda^2}{amt_{\rm self}} \qquad t_{\rm self} = \frac{m}{a\rho\sigma_{\rm self}\nu} \qquad a = \sqrt{\frac{16}{\pi}}$$ - collisional limit $\lambda \ll H$

$$\kappa_{\rm LMFP} = \frac{3}{2}C\frac{\rho H^2}{mt_{\rm self}} \qquad C = 0.75$$ - free-streaming limit $\lambda \gg H$

Iso-thermal halo

Self-scattering leads to thermalization of DM halos at $r < r_1$
where self-scattering happens at least one time until now

$$\sigma/m\,\rho(r_1)v(r_1)\,t_{\rm age} = 1$$



Core-collapse of SIDM

Two regimes of pure SIDM

Ann and Shapiro, MNRAS, 2005

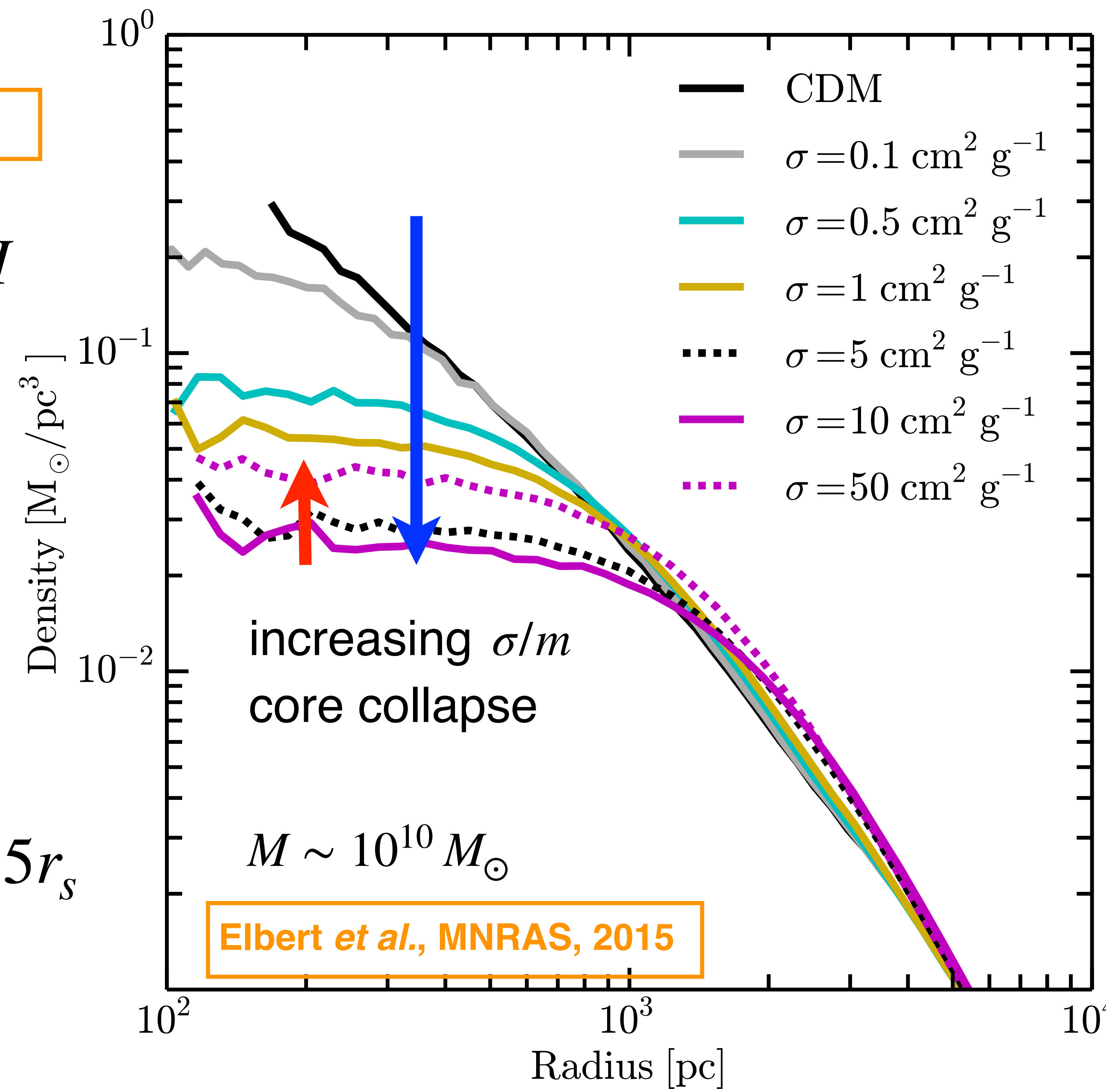
- free-streaming limit $\lambda \gg H$

  decreasing σ/m → CDM

- collisional limit $\lambda \ll H$

  increasing σ/m → CDM!

→ maximal core size $r_{\rm core} \lesssim 0.5 r_s$



Self-heating dark matter

One more important effect: heating

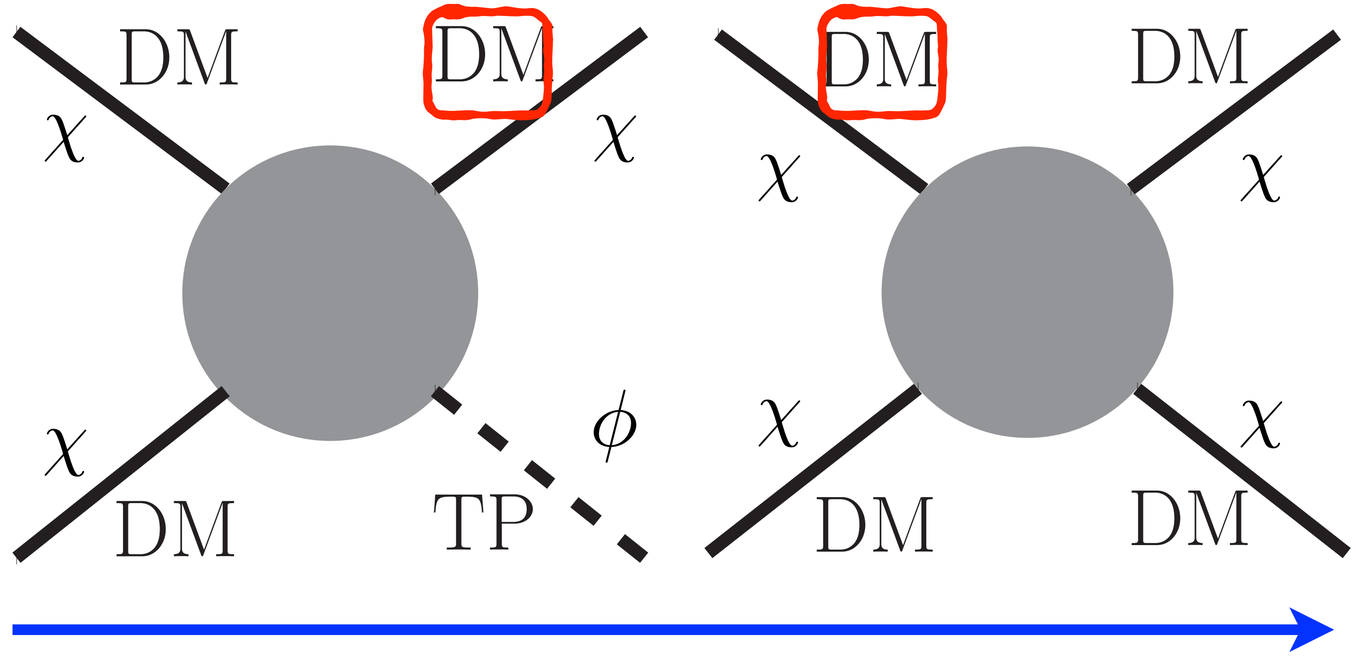
- make a difference from pure SIDM

Semi-annihilation

- only a tiny part of DM

Self-scattering

- sharing the mass deficit w/ others $m \gg T \sim mv^2$



- velocity dispersion

→ DM evaporation from the inner region of a halo

Self-heating: energy deposit

AK and Kim, arXiv:1911.09717

Energy deposit through semi-annihilation

$$\frac{\delta u_{\rm semi}}{\delta t} = \frac{\rho \langle \sigma_{\rm semi} v_{\rm rel} \rangle}{m} \frac{\xi \delta E}{m} \qquad \delta E = \frac{m}{4}$$

$$\xi = b \times \frac{r}{\lambda}\Big|_{r=r_s}$$ - deposit efficiency w/ a fudge factor b

$$\simeq 0.0002\, b \left(\frac{r_s}{3.43\ \rm kpc}\right)\left(\frac{\rho_s}{0.011\, M_\odot/{\rm pc}^3}\right)\left(\frac{\sigma_{\rm self}/m}{0.1\ {\rm cm}^2/{\rm g}}\right)$$

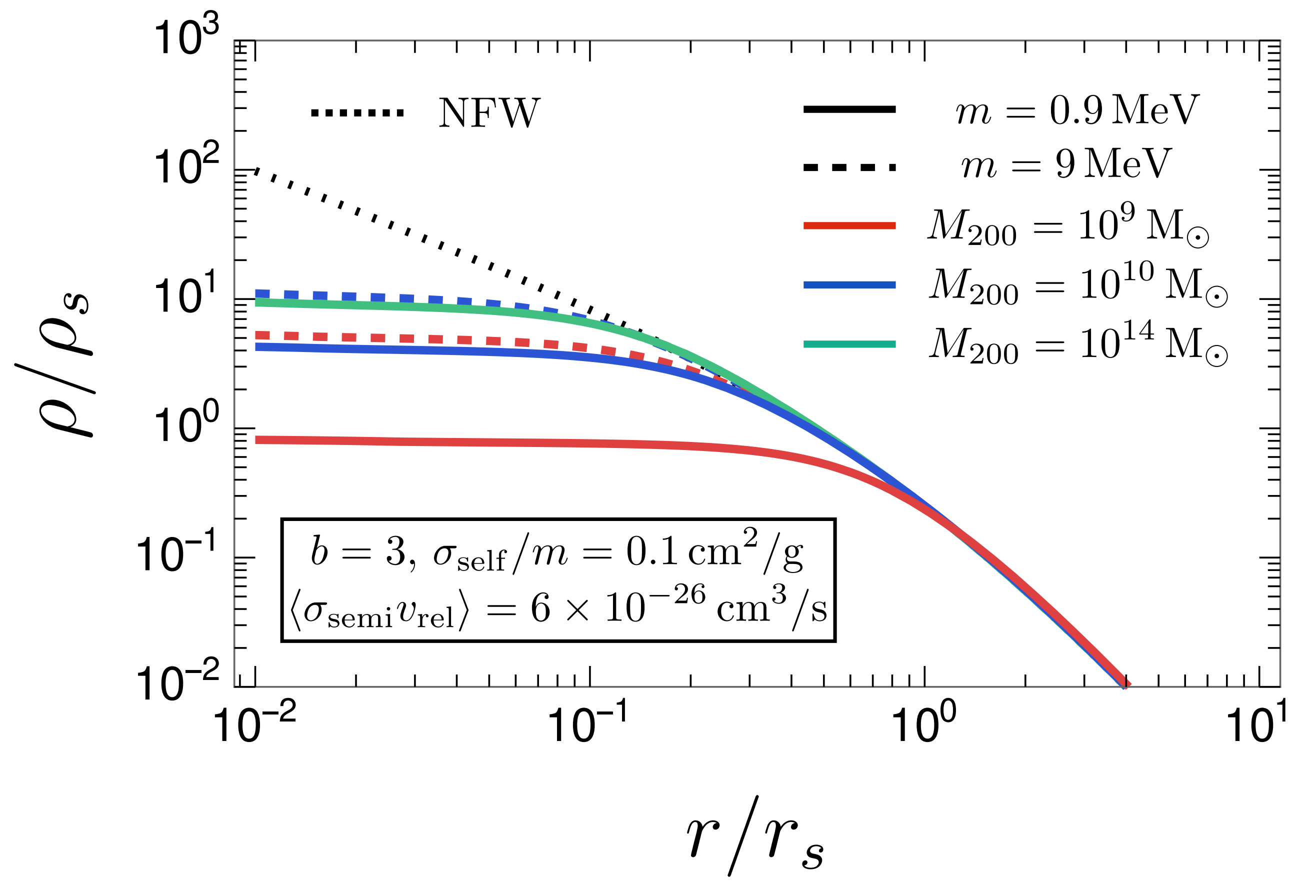
Heating time scale

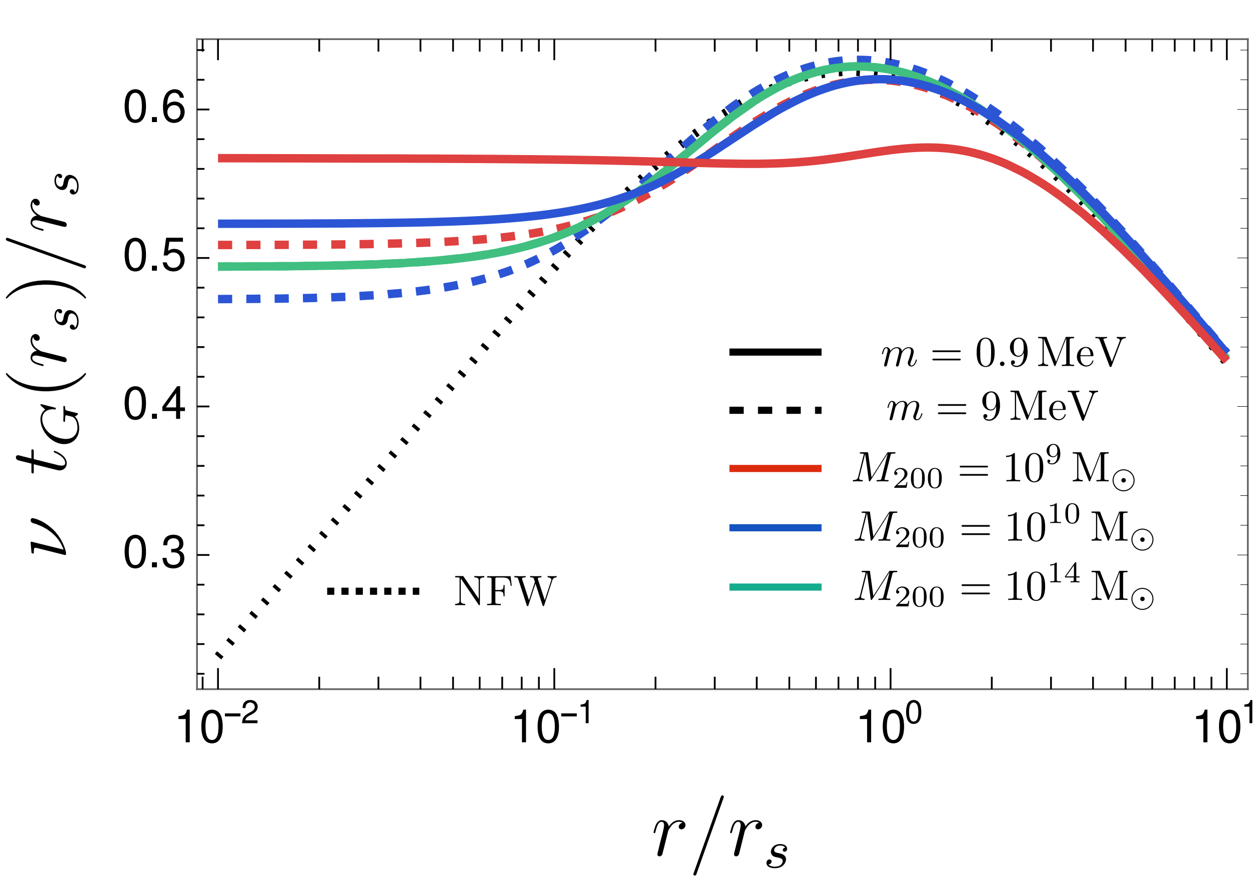
$$\frac{1}{\nu^2}\frac{\delta u_{\rm semi}}{\delta t} = \frac{\rho \langle \sigma_{\rm semi} v_{\rm rel} \rangle}{m} \frac{\xi \delta E}{m\nu^2} = \left(\frac{\nu_{\rm NFW}(r_s)}{\nu}\right)^2 \left(\frac{\rho}{\rho_{\rm NFW}(r_s)}\right)\frac{1}{t_{\rm heat}}$$

$$t_{\rm heat} \simeq \frac{138\ {\rm Gyr}}{b}\left(\frac{M_{200}}{10^9\ {\rm M}_\odot}\right)^{0.68}\left(\frac{m}{1\ {\rm MeV}}\right)\left(\frac{6\times 10^{-26}{\rm cm}^3/{\rm s}}{\langle \sigma_{\rm semi} v_{\rm rel}\rangle}\right)\left(\frac{0.1\ {\rm cm}^2/{\rm g}}{\sigma_{\rm self}/m}\right)$$

Sample halos

AK and Kim, arXiv:1911.09717





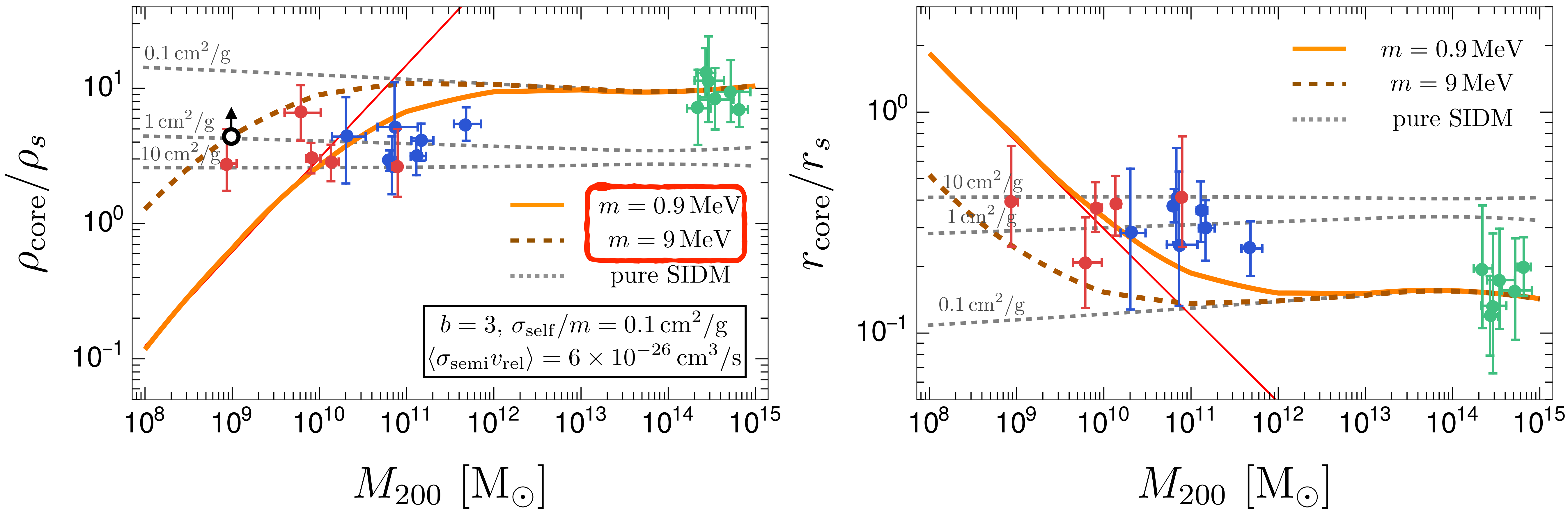
For given $\sigma_{\rm self}/m$ and $\langle\sigma_{\rm semi}v_{\rm rel}\rangle$

smaller m has a bigger impact toward smaller-size halos

$$t_{\rm heat} \simeq \frac{138\,\mathrm{Gyr}}{b}\left(\frac{M_{200}}{10^9\,\mathrm{M}_\odot}\right)^{0.68}\left(\frac{m}{1\,\mathrm{MeV}}\right)\left(\frac{6\times10^{-26}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma_{\rm semi}v_{\rm rel}\rangle}\right)\left(\frac{0.1\,\mathrm{cm}^2/\mathrm{g}}{\sigma_{\rm self}/m}\right)$$

Comparison w/ observations

AK and Kim, arXiv:1911.09717



Mimic velocity-dependent pure SIDM preferred by observations

for $m \sim 1\,\mathrm{MeV}$

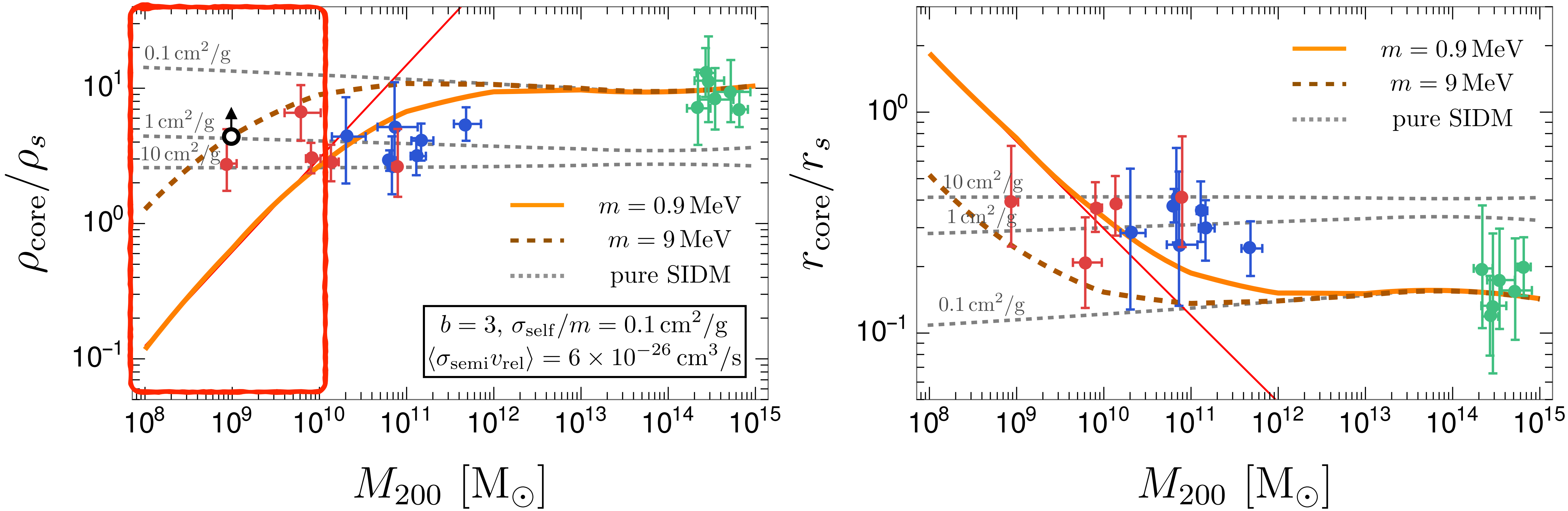
WDM constraints

$$m \simeq 60\,\mathrm{MeV} \left(\frac{T_\phi}{T_\gamma}\right)_{\rm eq} \left(\frac{m_{\rm WDM}}{5.3\,\mathrm{keV}}\right)^2 \left(\frac{\sigma_{\rm self}/m}{0.1\,\mathrm{cm}^2/\mathrm{g}}\right)^{1/2}$$

→ require hierarchical temperature $T_\phi \lesssim T_\gamma/100$

Comparison w/ observations

AK and Kim, arXiv:1911.09717



SHDM ↔ velocity-dependent SIDM? No!

- core-collapse $r_{\rm core} \lesssim 0.5 r_s$
- monotonically escalating impacts toward smaller-size halos

$$\rho_{\rm core}(t) \simeq 0.2\rho_s \cdot \left(t_{\rm heat}/t\right) \quad r_{\rm core}(t) \simeq 1.4 r_s \cdot \left(t/t_{\rm heat}\right)^{0.57}$$

→ differentiate SHDM and pure SIDM by smaller-size halos

- dwarf galaxies