Decaying ALPino dark matter as a solution to small scale issues

ALP: Axion-like particle, ALPino: fermionic partner of ALP
sALP: bosonic partner of ALP

Ayuki Kamada (IBS-CTPU)

기초과학연구원
Institute for Basic Science

Based on
Kyu Jung Bae, AK, Hee Jung Kim, arXiv:1806.08569

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Small-scale issues

Kentaro Nagamine's talk

Galactic matter distribution is difficult to explain in the cold dark matter (CDM) model Bullock *et al.*, Annu. Rev. Astron. Astrophys., 2018

- missing satellite problem Moore *et al.*, ApJ, 1999
  - observed number of dwarf spheroidal galaxies is $\mathcal{O}(10)$ times smaller than the prediction
- cusp vs core problem Moore *et al.*, MNRAS, 1999
  - low-surface brightness galaxies show ~ 2 times smaller inner rotation velocities than the prediction

Complex astrophysical processes may explain them

- gas heating from ionizing photons APSOTLE (Sawala *et al.*), MNRAS, 2016
- mass loss by supernova explosions NIHAO (Dutton *et al.*), MNRAS, 2016

while subgrid physics is unconstrained… FIRE (Wetzel *et al.*), ApJ, 2016

Small-scale issues - alternatives to CDM

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Alternatives to CDM are intriguing

- warm dark matter (WDM)

  $m_{\rm wdm} = \mathcal{O}(1)\,{\rm keV}$ Bode *et al.*, ApJ, 2001 Lovell *et al.*, MNRAS, 2012
- self-interacting dark matter (SIDM)

  $\sigma_{\rm sidm}/m = \mathcal{O}(1)\,{\rm cm}^2/{\rm g}$ Spergel *et al.*, PRL, 2000 Tulin *et al.*, Phys. Rept., 2018

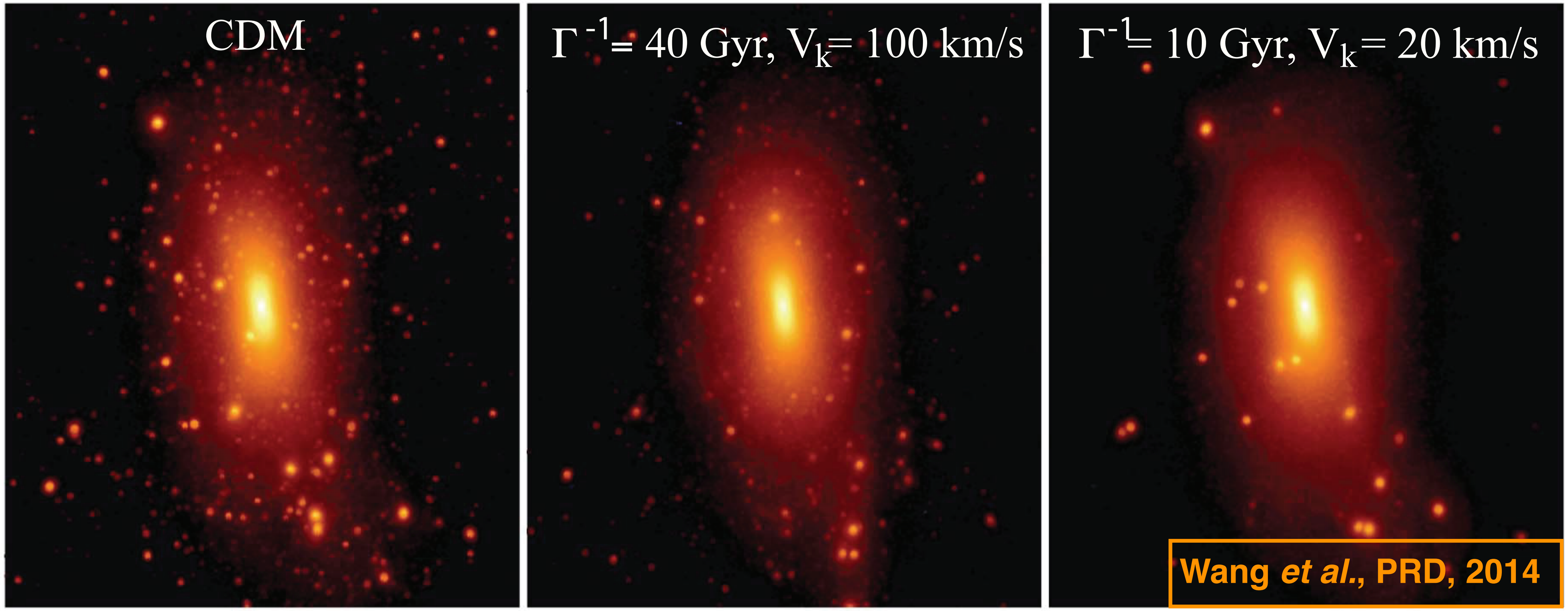
Late decaying dark matter I

heavy DM → light DM + light particle Peter *et al.*, PRD, 2010
w/ lifetime $\Gamma^{-1} \sim 10\,\mathrm{Gyr}$ and kick velocity $V_k = (m_h - m_l)/m_l \sim 20\,\mathrm{km/s}$

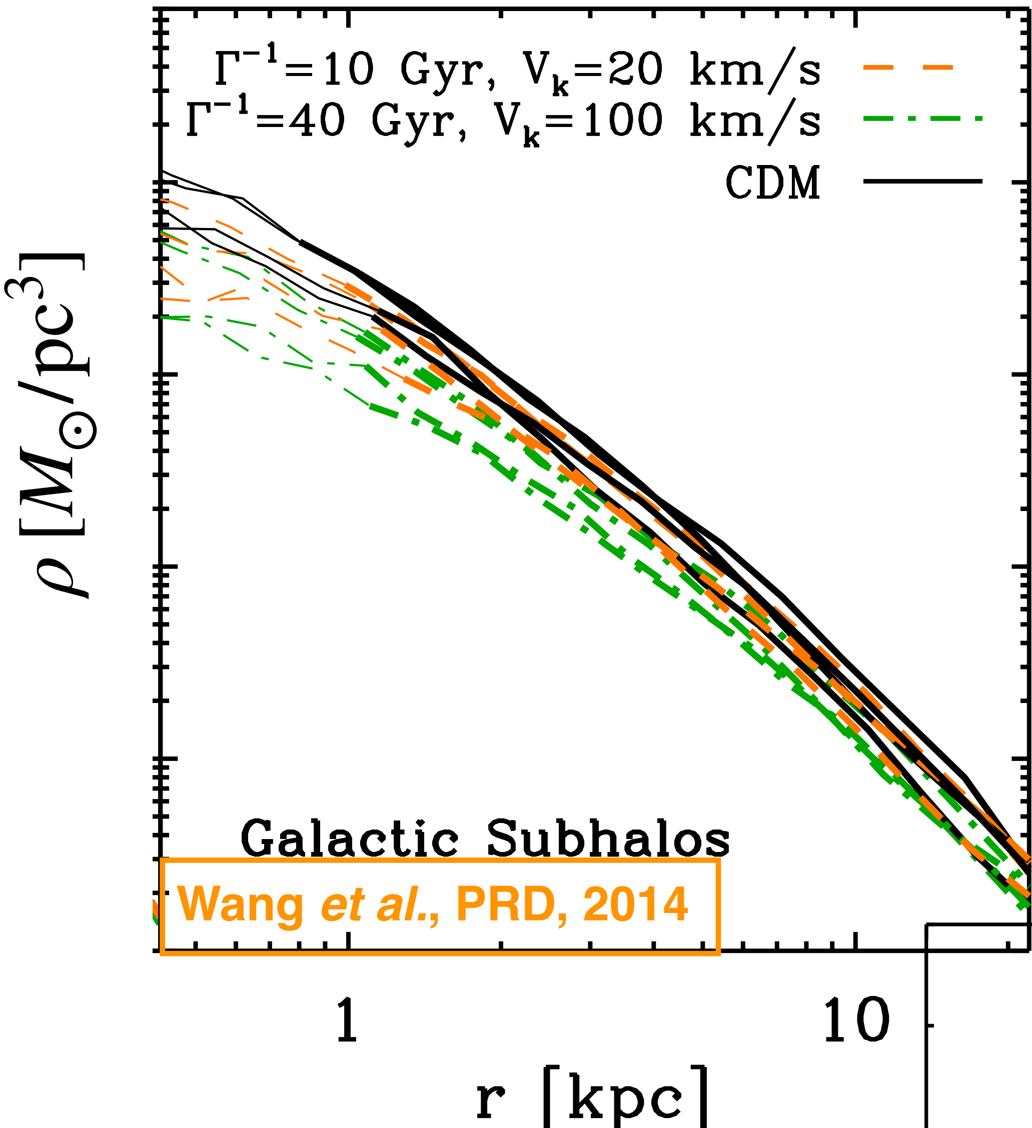
$\Omega_h h^2 \simeq \Omega_l h^2$ → CDM in large scale structure formation

missing satellite problem

$V_k \sim 20\,\mathrm{km/s}$ → evaporate dark matter from small-size halos

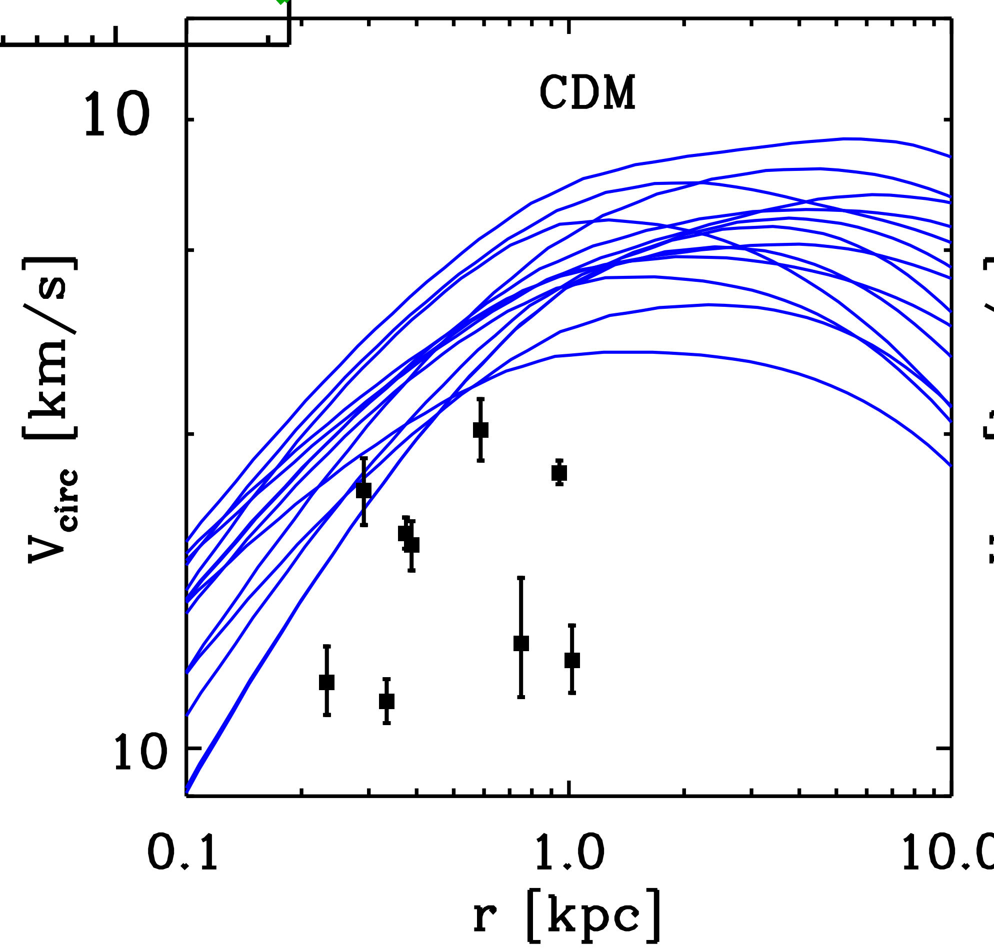


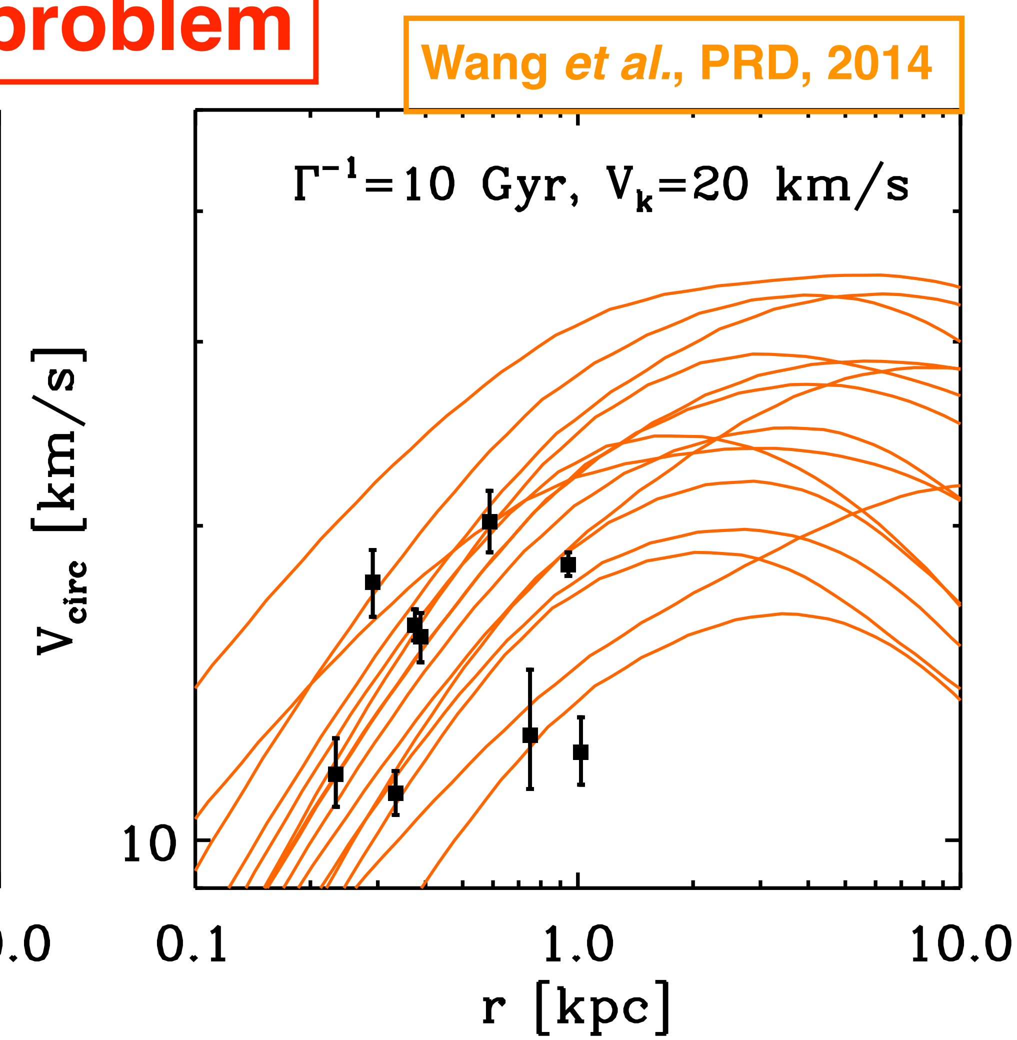
Late decaying dark matter II



cusp vs core problem

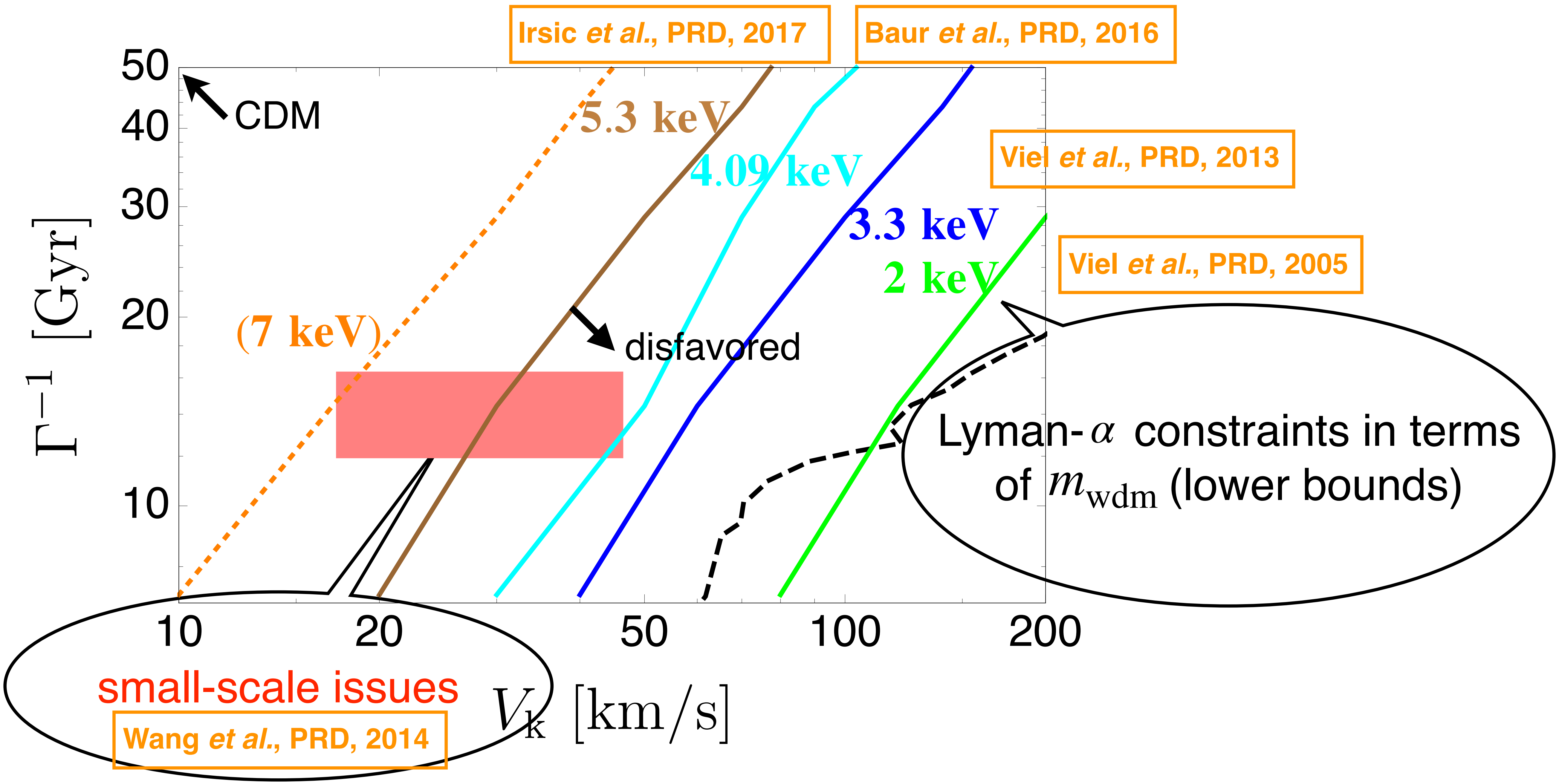
too big to fail problem





Lyman-α forest test

Lyman-α forests probe Mpc-scale matter distribution at $z \gtrsim 3$
decay fraction - $14\,\%$ at $z = 3$, $62\,\%$ at $z = 0$ for $\Gamma^{-1} \sim 10\,\mathrm{Gyr}$



Late decaying dark matter simultaneously explains the small-scale issues and Lyman-α forests data

Supersymmetric ALP model

ALP: (almost) massless and harmless
→ good candidate of the light decay product

minimal Kähler potential (✗ $|X|^2|S|^2/M_{\rm pl}^2$)
+ sequestered super potential $W \supset \lambda Z(XY - f^2) + W(S)$
→ $m_{\tilde{a}} = m_{3/2}\left[1 + \mathcal{O}\left(m_{3/2}^2/f^2\right)\right]$

Goto *et al.*, PLB, 1992
Chun *et al.*, PLB, 1992
Chun *et al.*, PLB, 1995

$W \supset kXQ\bar{Q}$
1-loop contribution → $\Delta m_{\tilde{a}} = \dfrac{k^2}{(4\pi)^2} m_{3/2}$
$k \sim 0.1$ → $V_k \sim 20\,\mathrm{km/s}$

ALPino mass is degenerate with gravitino mass

integrating out Q → $W_{\rm eff} \supset -\sqrt{2} g_{aB}\, A\, W_B W_B - \sqrt{2} g_{ag_{\rm h}}\, A\, W_{\rm h}^a W_{\rm h}^a$

hypercharge superfield
→ ALPino production
→ALP-photon conversion

hidden confinement gauge field
→ ALP mass

ALPino decay into gravitino + ALP

Decay operator: $\mathscr{L}_{3/2} = -\frac{1}{2M_{\rm pl}}\partial_\nu a\,\bar{\psi}_\mu\gamma^\nu\gamma^\mu i\gamma_5\,\tilde{a}$

Cremmer *et al.*, Nucl. Phys. B, 1983

$$\rightarrow \quad \Gamma_{\tilde{a}}^{-1} = \frac{96\pi m_{3/2}^2 M_{\rm pl}^2}{m_{\tilde{a}}^5}\left(1-\frac{m_{3/2}}{m_{\tilde{a}}}\right)^{-2}\left(1-\frac{m_{3/2}^2}{m_{\tilde{a}}^2}\right)^{-3}$$

$$\simeq 10\,{\rm Gyr}\left(\frac{700\,{\rm TeV}}{m_{\tilde{a}}}\right)^3\left(\frac{20\,{\rm km/s}}{V_{\rm k}}\right)^5$$

Hamaguchi *et al.*, PLB, 2017

ALPino/gravitino mass determined to be sub-PeV!

PeV-scale MSSM particles → $m_h \simeq 125\,{\rm GeV}$

Giudice *et al.*, Nucl. Phys. B, 2012

ALP production from LOSP decay

PeV-scale lightest ordinary supersymmetric particle (LOSP) decays into ALPino $W_{\rm eff} \supset -\sqrt{2} g_{aB} A\, W_B W_B$

→ too large relic density

$$Y_{\rm losp}^{\rm fo} \simeq 4 \times 10^{-13} \left(\frac{m_{\rm losp}}{1\,{\rm TeV}} \right)$$ for $\sigma v \simeq \dfrac{\pi\alpha^2}{m_{\rm losp}^2}$ like wino

↔ $$Y_{\tilde a}^{\rm obs} \simeq 6 \times 10^{-16} \left(\frac{700\,{\rm TeV}}{m_{\tilde a}} \right)$$

Freeze-out before reheating → dilution

$$Y_{\tilde a} \sim Y_{\rm losp}^{\rm fo} \left(\frac{T_{\rm R}}{T_{\rm fo}} \right)^3 \rightarrow T_{\rm R} \sim 570\,{\rm GeV} \left(\frac{m_{\rm losp}}{1\,{\rm PeV}} \right)^{2/3} \left(\frac{700\,{\rm TeV}}{m_{\tilde a}} \right)^{1/3}$$

Monochromatic ALP flux

ALPino decay into gravitino + ALP
→ monochromatic ALP flux with

$$E_a = m_{\tilde{a}} V_{\mathrm{k}} \simeq 47\,\mathrm{GeV} \left(\frac{m_{\tilde{a}}}{700\,\mathrm{TeV}}\right) \left(\frac{V_{\mathrm{k}}}{20\,\mathrm{km/s}}\right)$$

$$E_a^2 \frac{d^2\Phi_a}{dE_a d\Omega} \simeq 2 \times 10^2\,\mathrm{MeV/cm^2/s/sr} \left(\frac{E_a}{47\,\mathrm{GeV}}\right)^2 \left(\frac{700\,\mathrm{TeV}}{m_{\tilde{a}}}\right)$$

for $\Gamma_{\tilde{a}}^{-1} \sim 10\,\mathrm{Gyr}$

10^6 times larger

$l = 0\text{-}360^\circ\,,\ \ |b| = 8\text{-}90^\circ\,,\ \ \Delta E = 20\,\mathrm{GeV}$

Fermi-LAT gamma-ray flux $E_\gamma^2 \frac{d^2\Phi_\gamma^{\mathrm{obs}}}{dE_\gamma d\Omega} \simeq 6 \times 10^{-4}\,\mathrm{MeV/cm^2/s/sr}$

ALP-photon conversion

ALP-photon conversion in Galactic magnetic field

$$W_{\rm eff} \supset -\sqrt{2}\, g_{aB}\, A\, W_B W_B$$

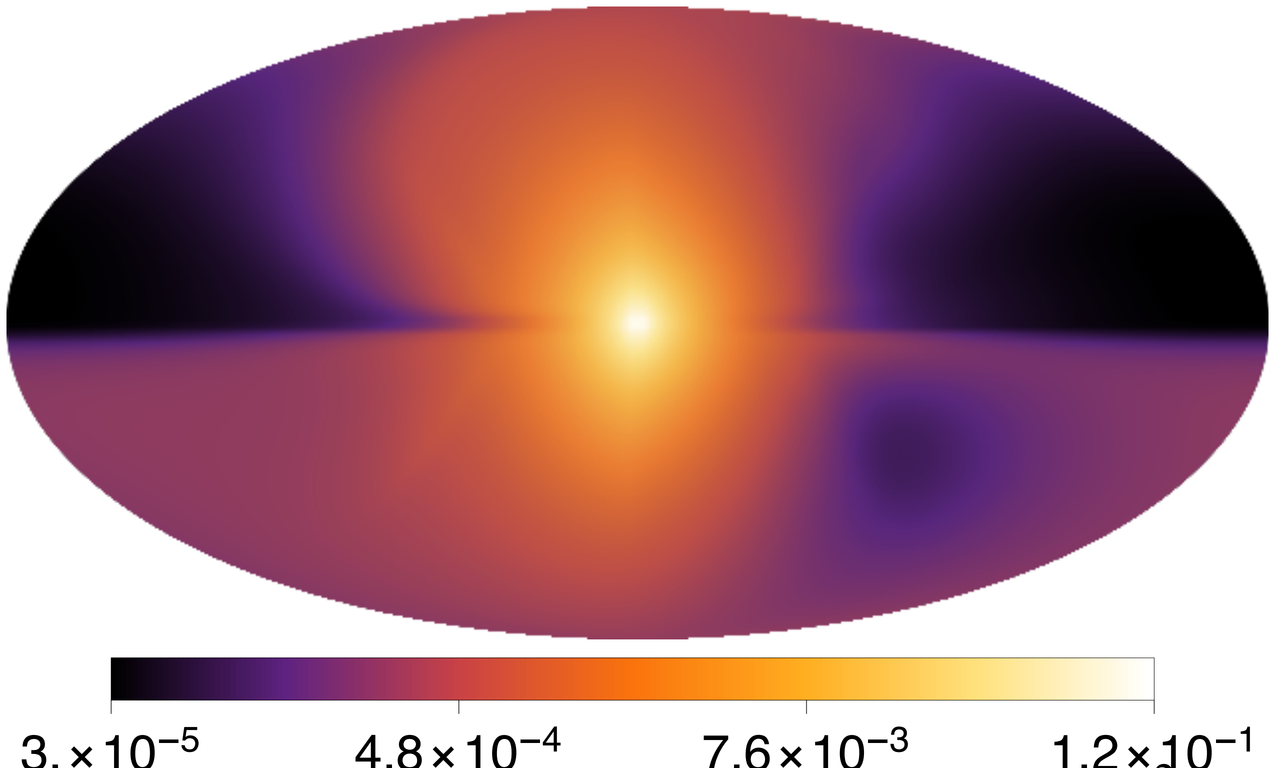
→ (adiabatic) conversion rate

Raffelt *et al.*, PRD, 1988

$$P_{a\gamma}(s,\Omega) \simeq 2\times10^{-7} \left|\frac{B_T(s,\Omega)}{\mu\mathrm{G}}\right|^2 \left(\frac{10^{-8}\,\mathrm{eV}}{m_a}\right)^4 \left(\frac{g_{a\gamma}}{10^{-13}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{E_\gamma}{47\,\mathrm{GeV}}\right)^2$$

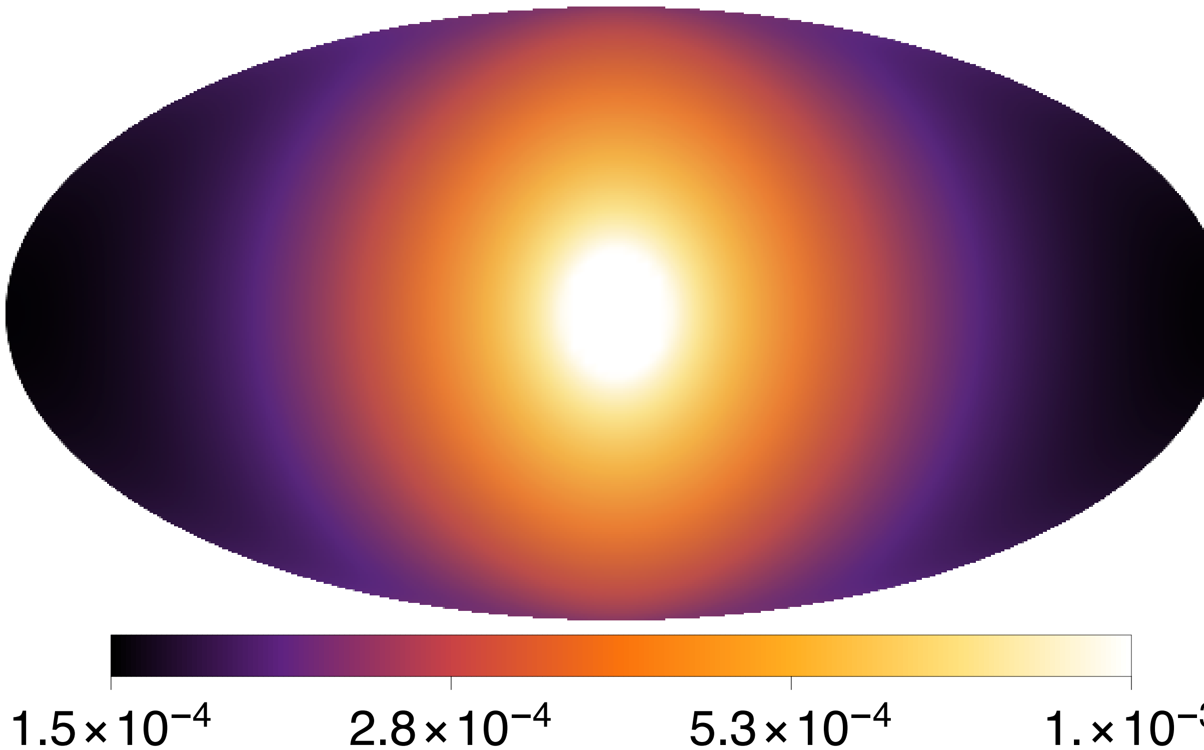
Distinctive morphology - convolution of magnetic field distribution and dark matter distribution

Janson *et al.*, ApJ, 2012



decay + conversion

$E_\gamma^2 \frac{d^2\Phi_\gamma}{dE_\gamma d\Omega}$ [MeV/cm^2/s/sr]



direct decay

Summary and future works

Late decaying dark matter w/ $\Gamma^{-1} \sim 10\,\mathrm{Gyr}$ and $V_k \sim 20\,\mathrm{km/s}$
- unchange the CDM success in large-scale structure formation
- alleviating small-scale issues while evading Lyman-α forest test

→ more dedicated study and further tests are needed

ALPino → gravitino + ALP
- ALPino/gravitino mass $m \simeq 700\,\mathrm{GeV}$
- ALPino produced by the decay of the frozen-out LOSP
- monochromatic $E = mV_\mathrm{k} \simeq 47\,\mathrm{GeV}$ gamma-ray flux through ALP-photon conversion
- unique morphology essential to differentiate this scenario from the baryon feedback as a solution to small scale issues

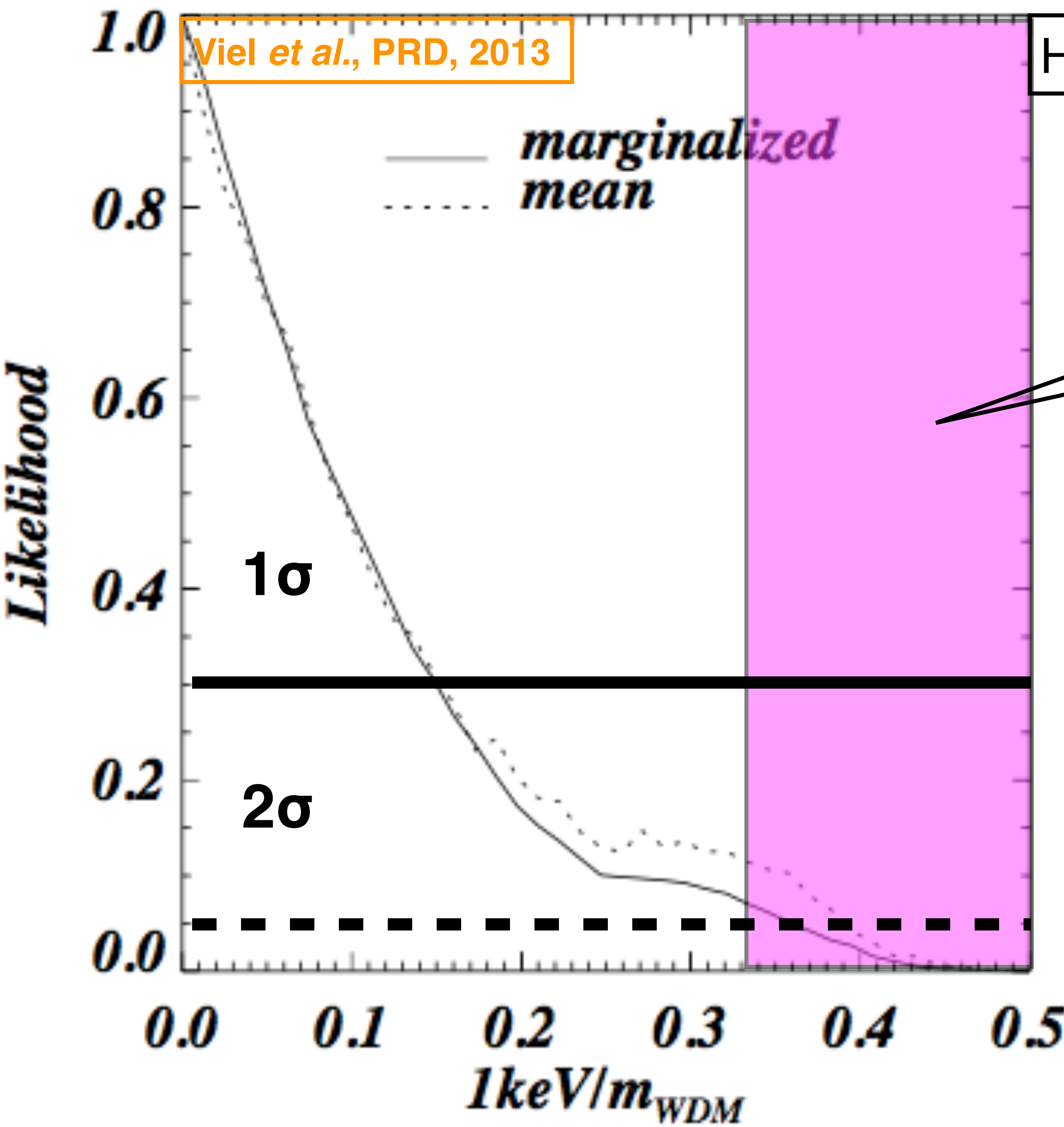
→ non-adiabatic photon-ALP conversion and more optimized analysis of Fermi-LAT data are worth investigating

Thank you for your attention

Backup slides

Lyman-α forest test for WDM

Lyman-α forests probe Mpc-scale matter distribution at $z \sim 4$



HIRES+MIKE 25 QSO (z>4) spectra

reconciling missing satellite problem $m_{\rm wdm} \lesssim 3\,{\rm keV}$

Schneider, MNRAS, 2015

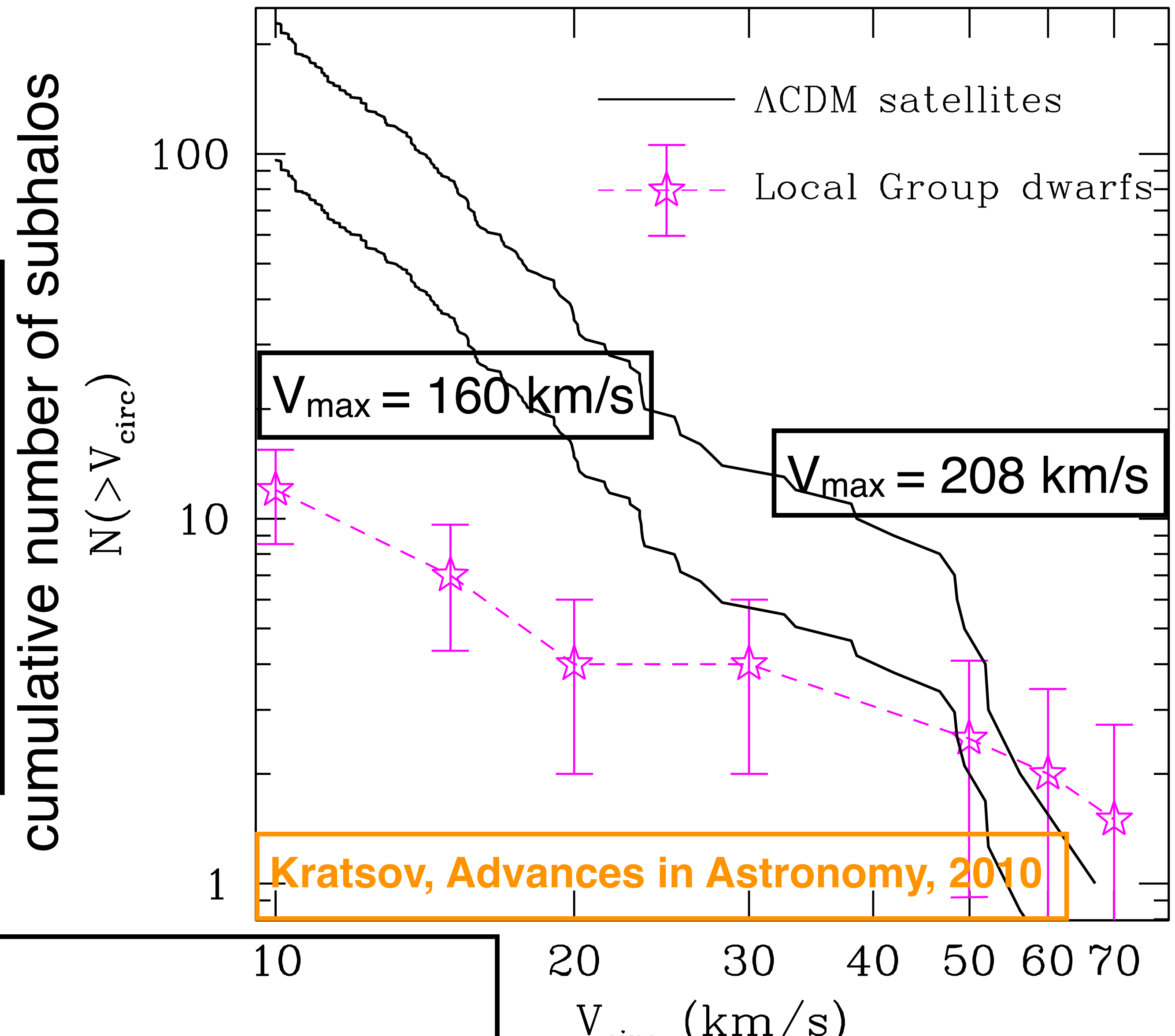
WDM appears not to simultaneously explain the missing satellite problem and Lyman-α forests data

Small scale crisis I

When *N*-body simulations in the ΛCDM model and observations are compared, problems appear at (sub-)galactic scales: **small scale crisis**

missing satellite problem

N-body (DM-only) simulations in the ΛCDM model → Milky Way-size halos host O(10) times larger number of subhalos than that of observed dwarf spheroidal galaxies



maximal circular velocity of subhalo

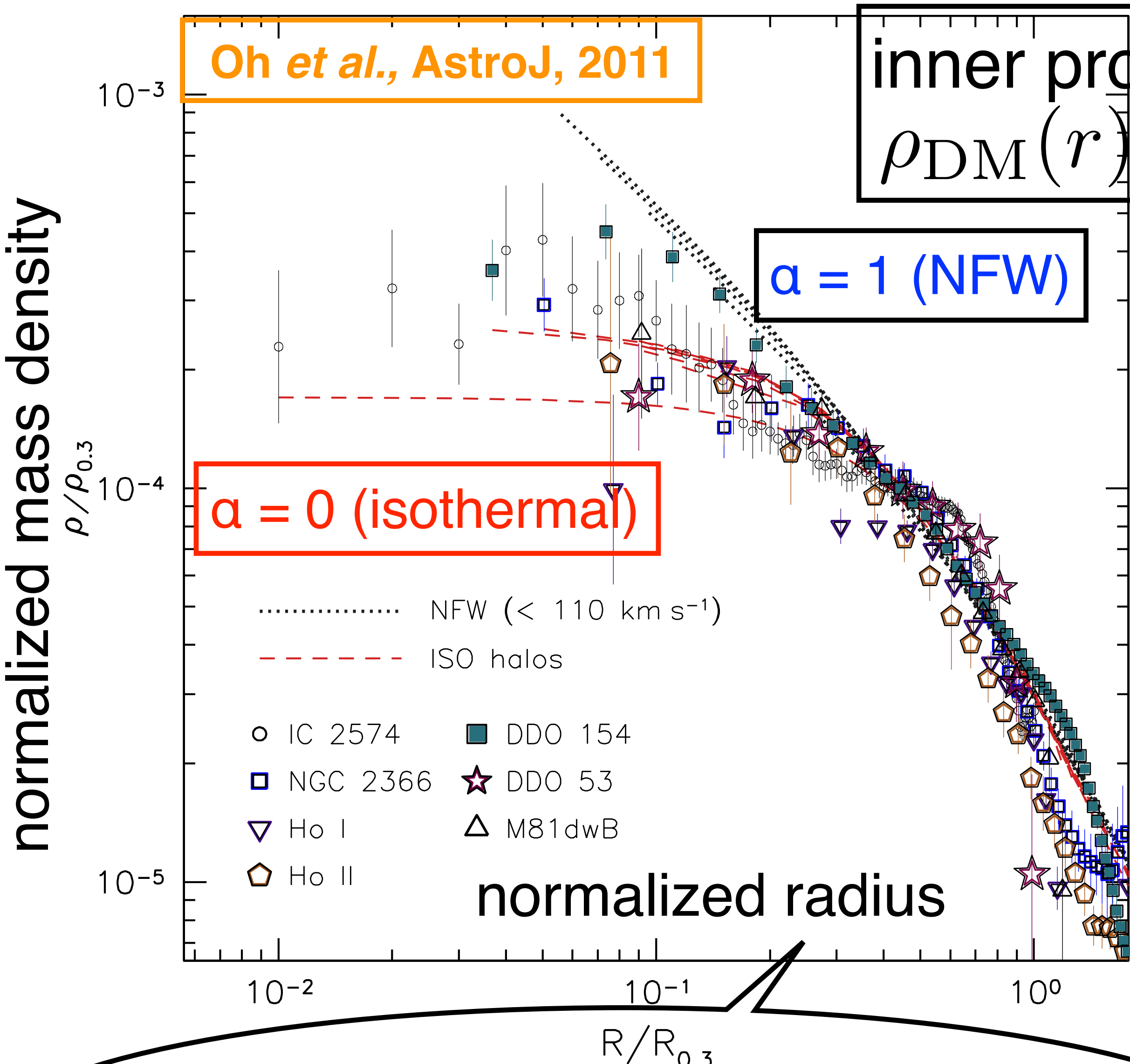
(maximum) circular velocity

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

Small scale crisis II

cusp vs core problem

N-body (DM-only) simulations in the ΛCDM model → common DM profile independent of halo size: NFW profile



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

field dwarf spheroidal galaxies
~10^9 Msun

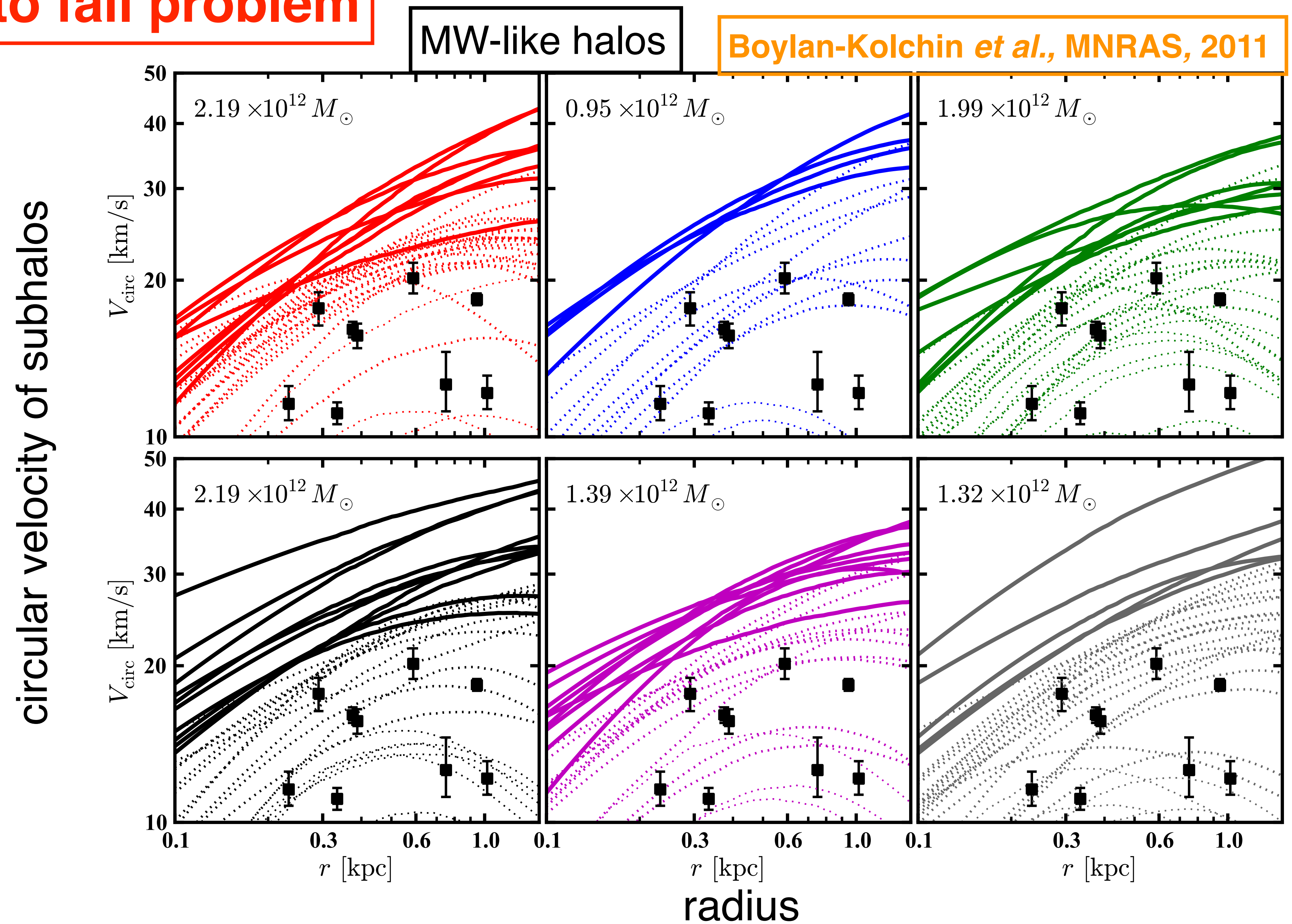
Observations infer cored profile in the inner region rather than cuspy NFW profile

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



N-body (DM-only) simulations in the ΛCDM model →
~10 subhalos with deepest potential wells in Milky Way-size halos
do not host observed counterparts (dwarf spheroidal galaxies)

Caveat on WDM

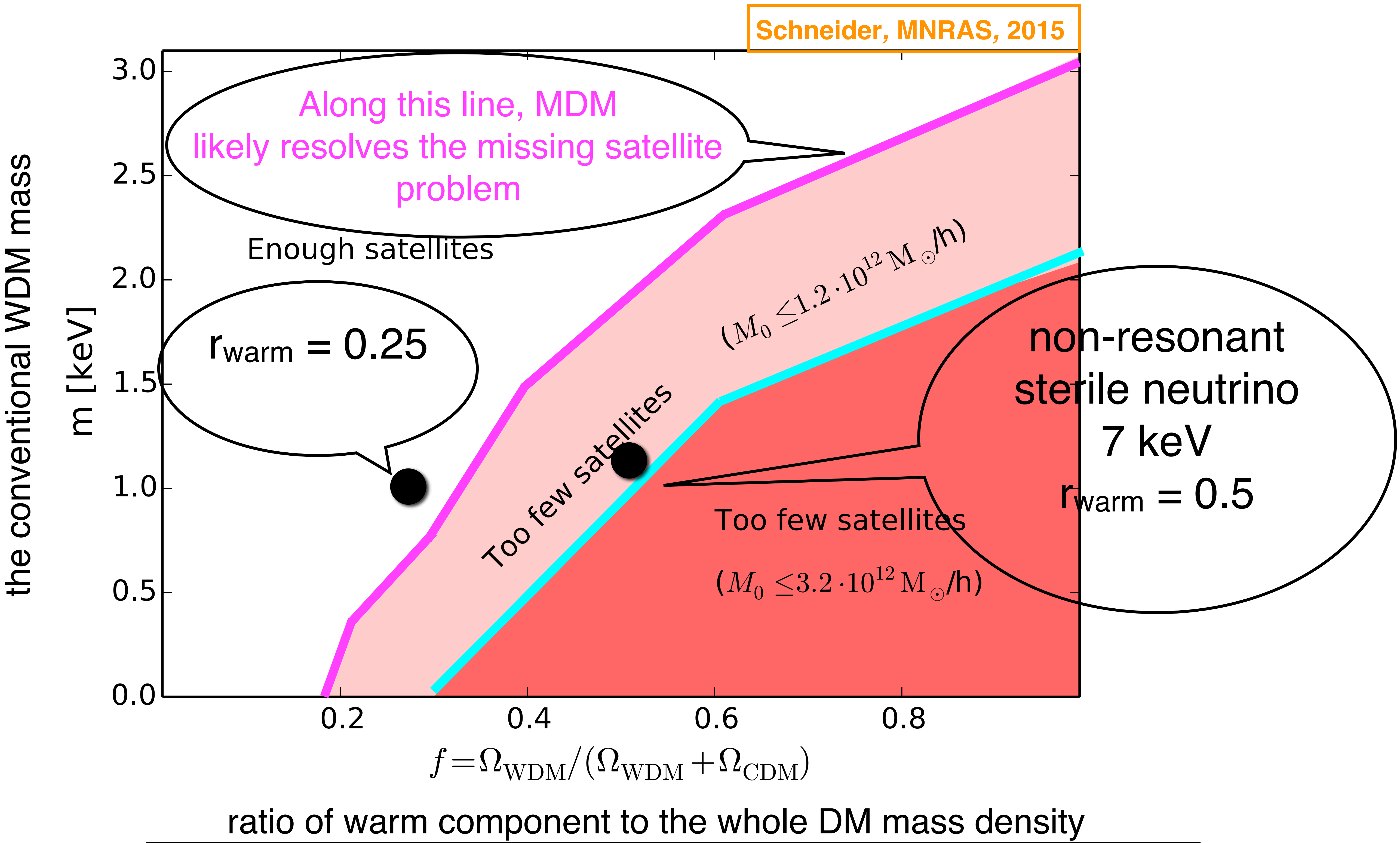
BE CAREFUL OF what is called the *thermal warm dark matter* conventionally!
The WDM particles follow the Fermi-Dirac distribution $f_{\rm WDM} = \frac{1}{e^{p/T_{\rm WDM}} + 1}$
and have two spin degrees of freedom.
The temperature is determined $\rho_{\rm WDM} = m_{\rm WDM} \times 2 \int \frac{d^3p}{(2\pi)^3} f_{\rm WDM}$
to reproduce a given (observed) DM mass density
for a given WDM mass: $\Omega_{\rm warm} h^2 = \left(\frac{m_{\rm WDM}}{94\,{\rm eV}}\right) \left(\frac{T_{\rm WDM}}{T_\nu}\right)^3$

The constraint is often reported in terms of an lower bound on the WDM mass like $m_{\rm WDM} > 3.3\,{\rm keV}$ **M. Viel *et al.*, PRD, 2013**
but **it is NOT DIRECTLY APPLICABLE to your model!**
The implicitly assumed temperature: $\left(\frac{T_{\rm WDM}}{T_\nu}\right)^3 \simeq 0.01 \left(\frac{\Omega_{\rm warm} h^2}{0.12}\right) \left(\frac{\rm keV}{m_{\rm WDM}}\right)$

The early decoupling (before the electroweak phase transition)
is **NOT ENOUGH** to reproduce the assumed temperature $\frac{g_{*,\rm WDM}}{g_{*,\nu}} \simeq 0.1$

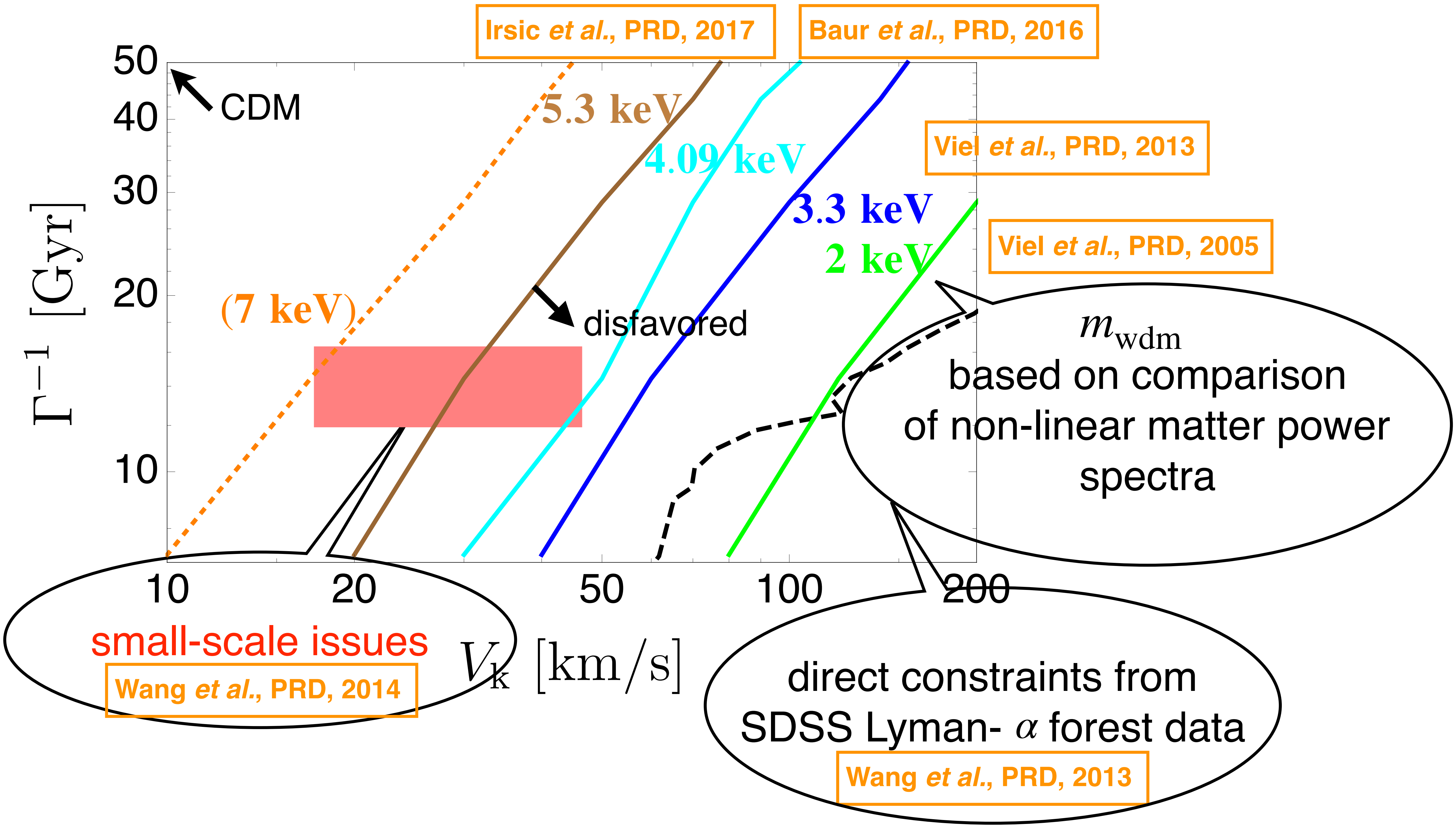
The conventional warm dark matter is **COLDER** than yours.
↔The lower bound in your warm dark matter mass is **LARGER**.

missing satellite problem in MDM models



Let us take two benchmark lines corresponding to smaller and larger MW masses

Lyman-α forest test (continued)



Non-linear matter power spectra
- fitting function for WDM Inoue *et al.*, MNRAS, 2015
- semi-analytic model for late-decaying dark matter Cheng *et al.*, JCAP, 2015

Parameter space