Beyond-WIMP DM models and constraints from anomalous strong-lens systems

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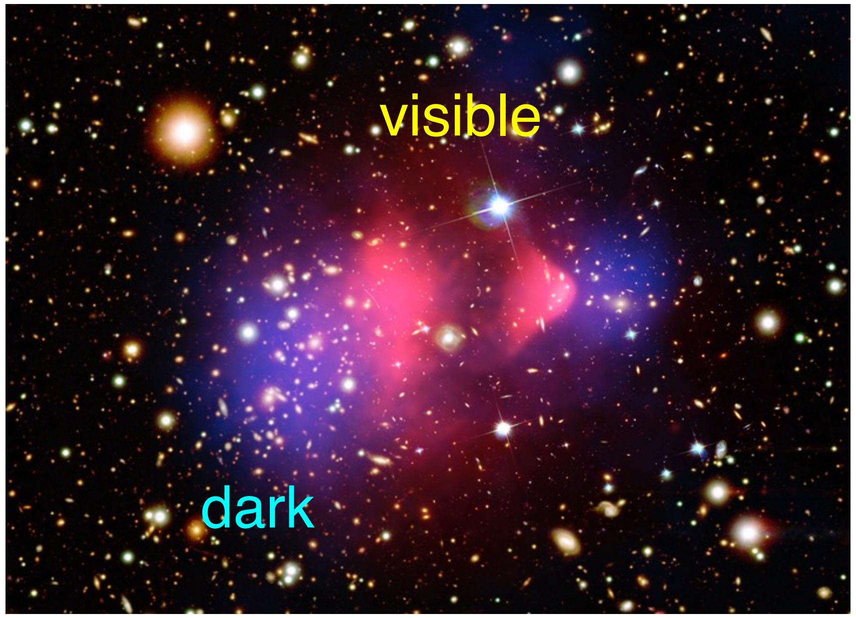
Based on
Akira Harada and AK, JCAP, 2016
AK, Kaiki Taro Inoue, and Tomo Takahashi, PRD, 2016
Kyu Jung Bae, AK, Hee Jung Kim, PRD, 2019
work in progress w/ Kaiki Taro Inoue …

Feb. 1, 2021 @ Time-Domain Cosmology with Strong Gravitational Lensing

Dark matter

Evident from cosmological observations

- cosmic microwave background (CMB)…

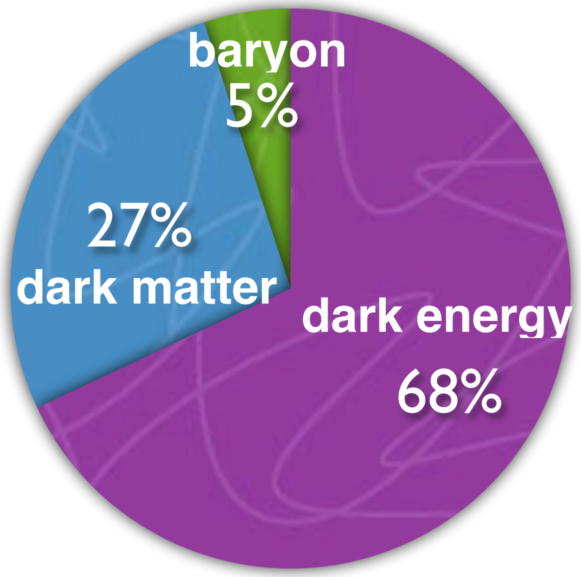


bullet cluster

Essential to form galaxies in the Universe

One of the biggest mysteries

- astronomy, cosmology, particle physics…



cosmic energy budget

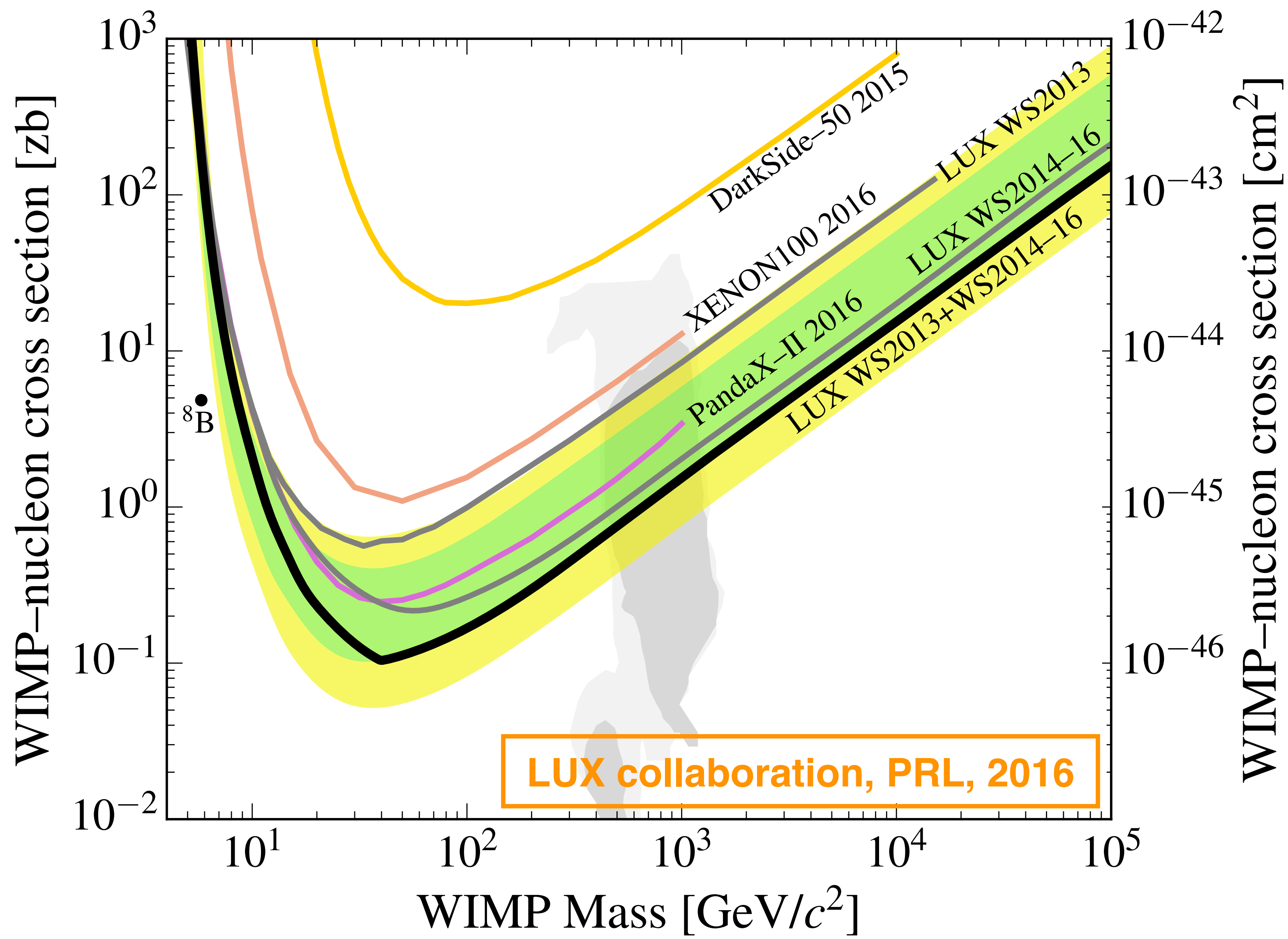
Dark matter search

Past 30+ years: search for weak interactions (WIMP) w/ visible particles

- miraculously well-motivated by particle physics

- LHC, direct and indirect detection experiments…

- not discovered yet → beyond WIMP?



Gravitational probes of dark matter

Collisionless cold dark matter

- minimal hypothesis on dark matter

- any deviations may hint the nature of dark matter (e.g., interaction and mass)

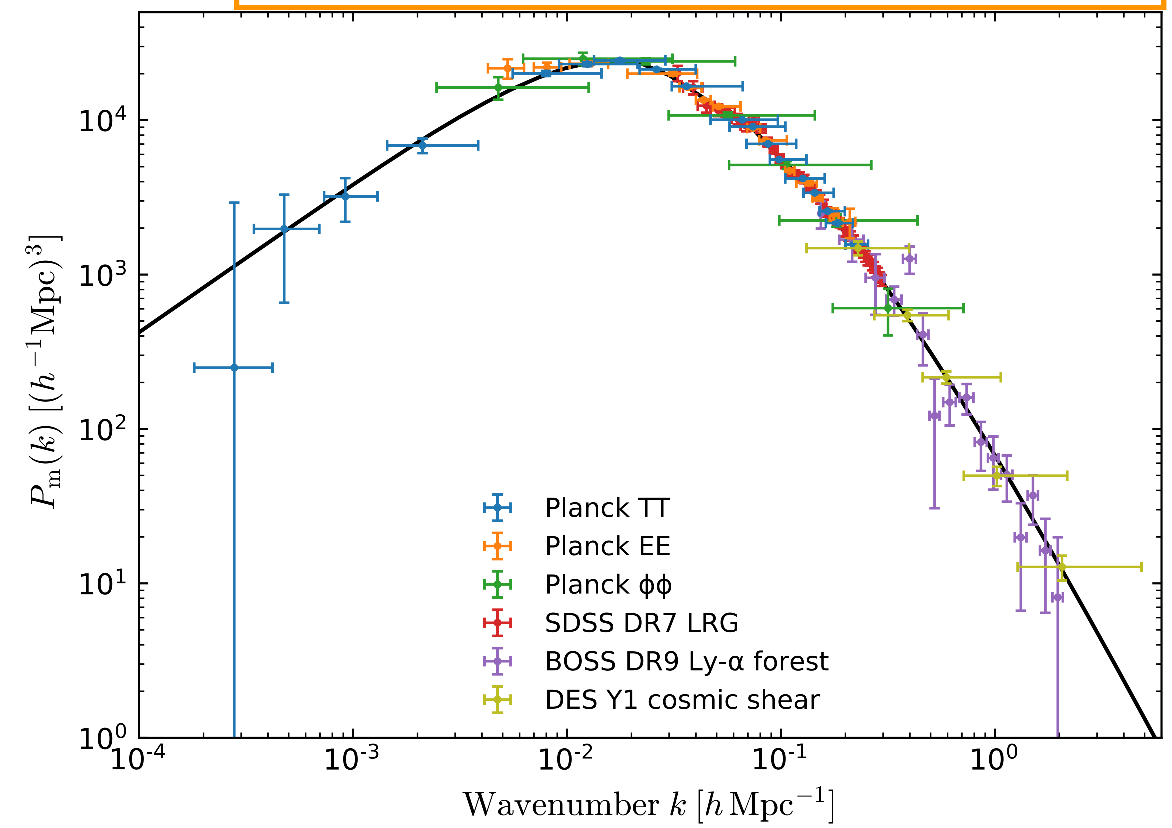
Large scales

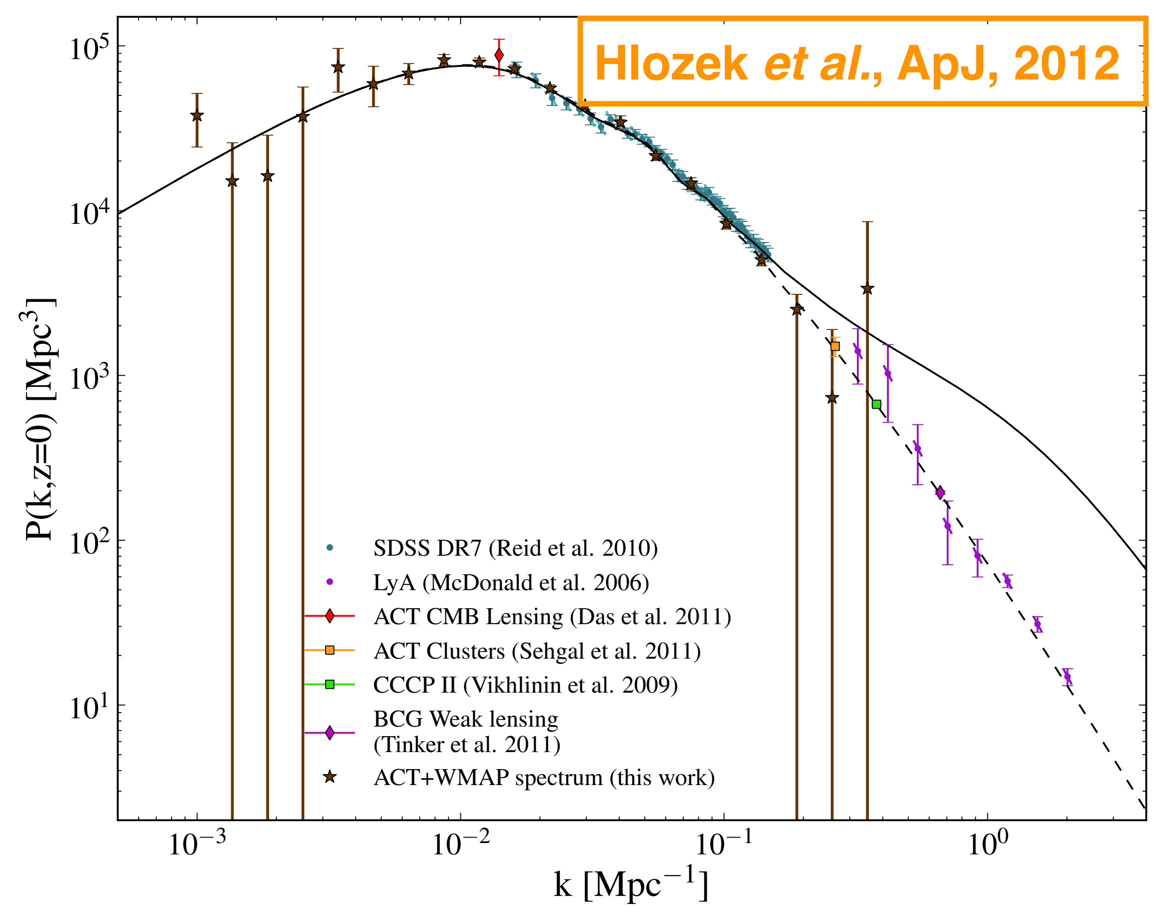
- explain observations over 3 orders of magnitude in length

$$10^{-3} < k\,[h/\mathrm{Mpc}] < 1$$

- cross-check our understanding of non-linear gravitational dynamics

Planck collaboration, arXiv:1807.06205





Hlozek *et al.*, ApJ, 2012

Galactic scales

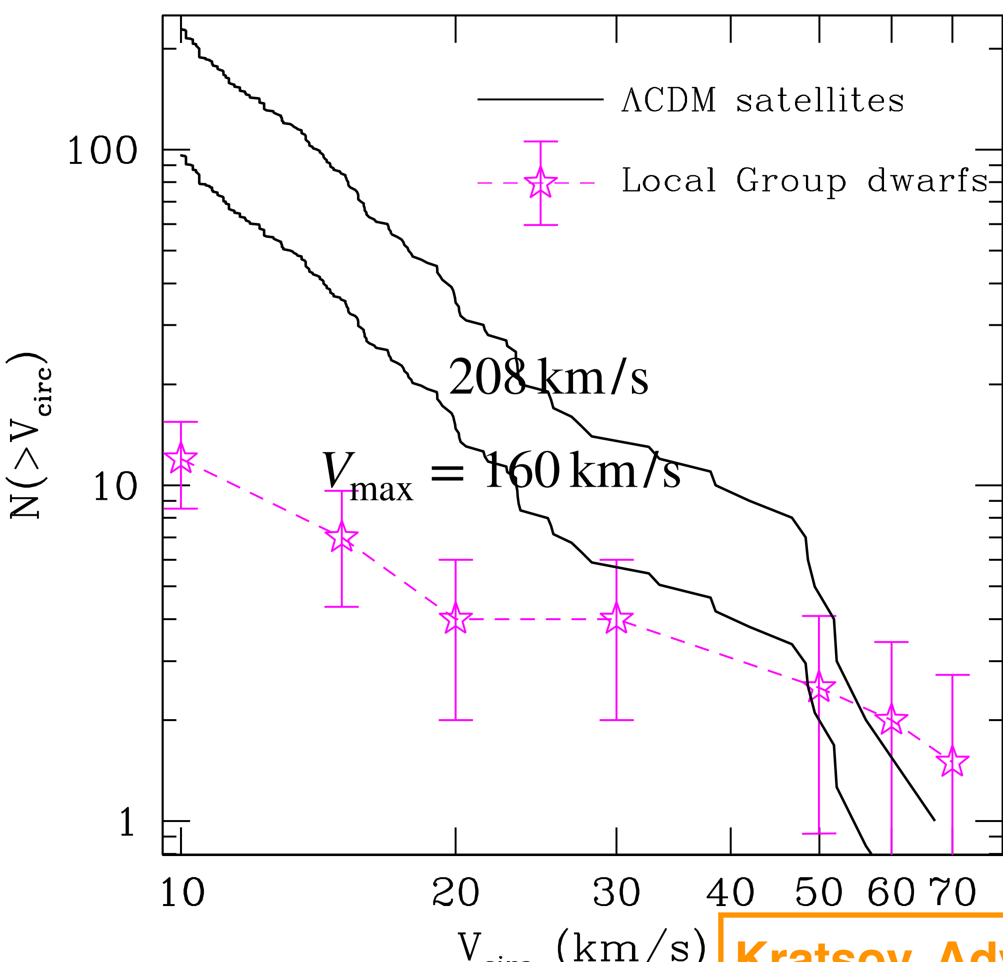
Small-scale issues?

- missing satellite, core cusp, too big to fail…

- naive CDM prediction does not work

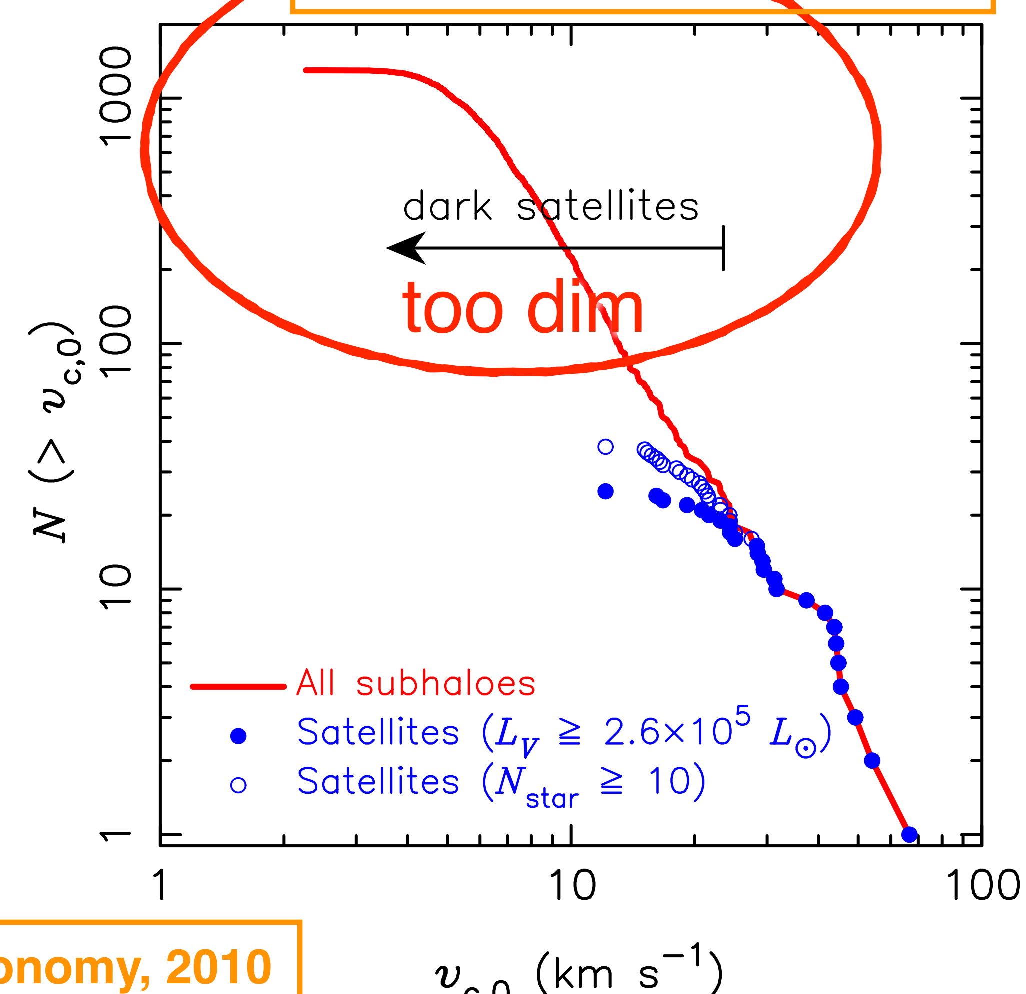
- may be attributed to unconstrained astrophysical processes

Missing satellite problem



Kratsov, Advances in Astronomy, 2010

Okamoto *et al.*, MNRAS, 2009



Galactic scales

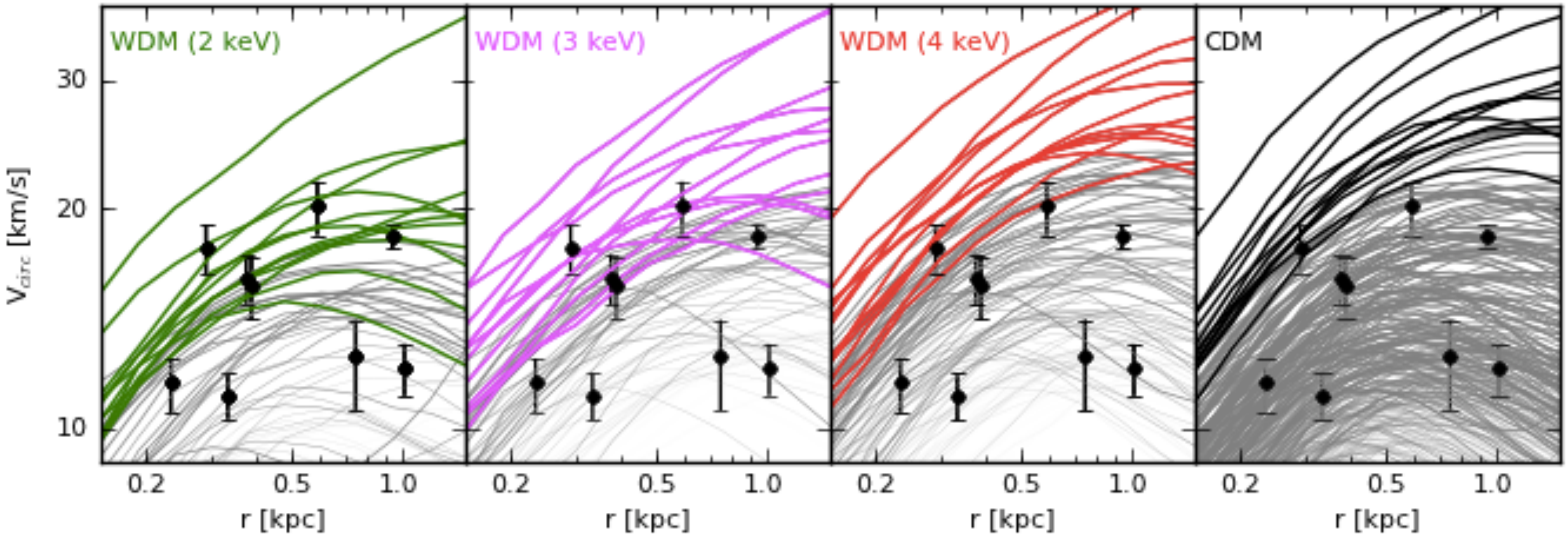
Nature of dark matter?

- warm (WDM), self-interacting (SIDM), decaying (DDM)…
- cross-check by other observations

WDM and too big to fail problem

- $m_{\mathrm{WDM}} \sim 2\,\mathrm{keV}$ solves the missing satellite and too big to fail problems
    - $m_{\mathrm{WDM}} \sim 0.5\,\mathrm{keV}$ for the core cusp problem

Schneider, Anderhalden, Maccio, and Diemand, MNRAS, 2014



Strong-lens system

Flux anomaly

See the talks by Daniel Gilman and Kaiki Taro Inoue

- fit lens potential to image positions

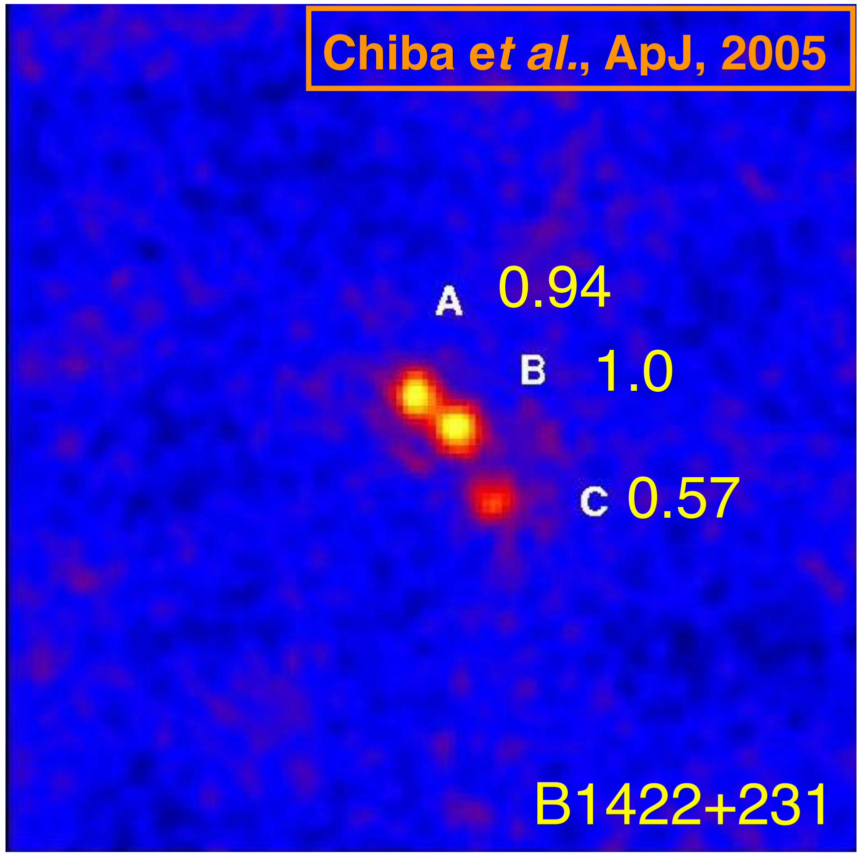
→ predict flux ratios (A+C)/B=1

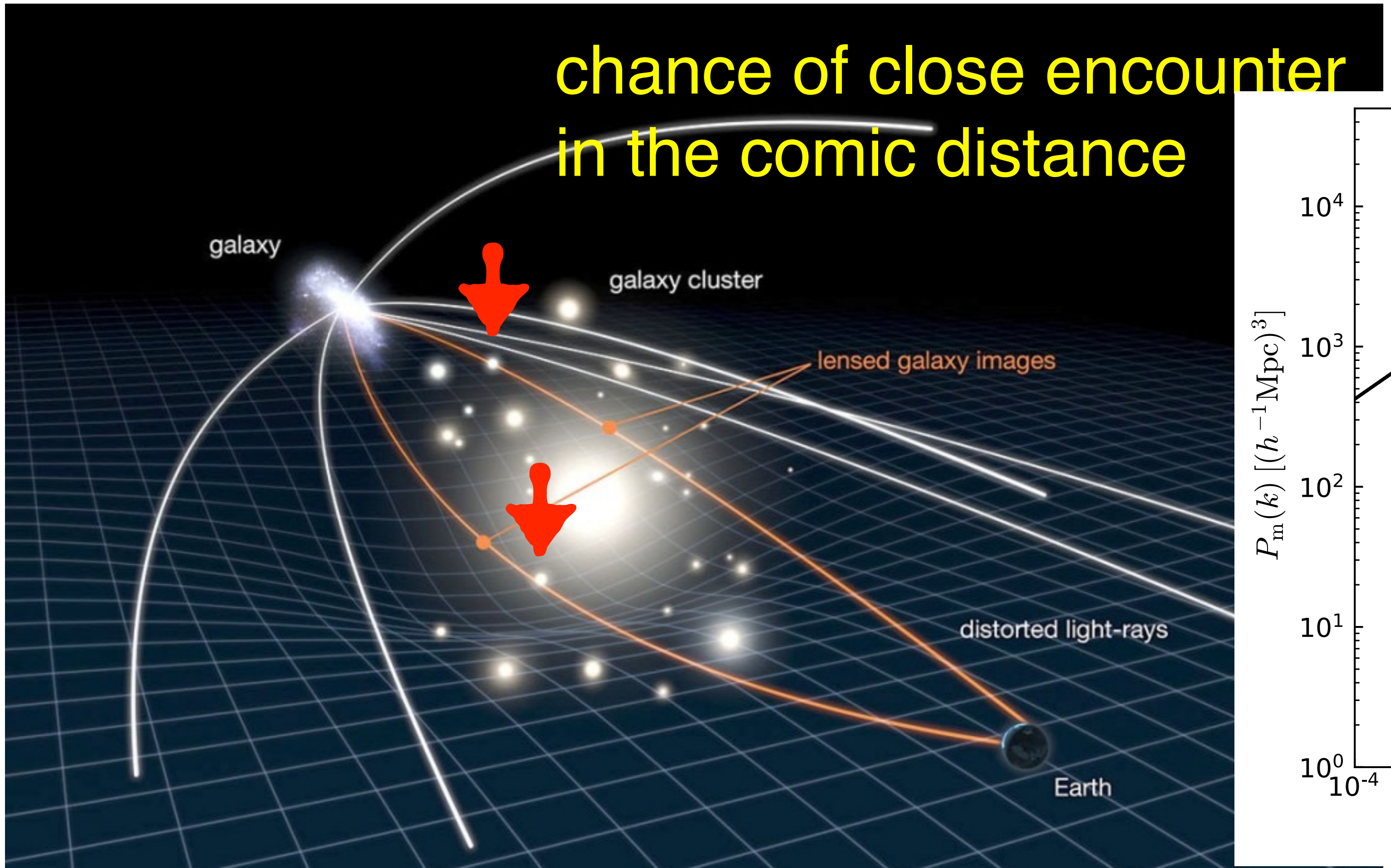
- observed (A+C)/B=1.5

- disturbed by l.o.s. halos & substructure

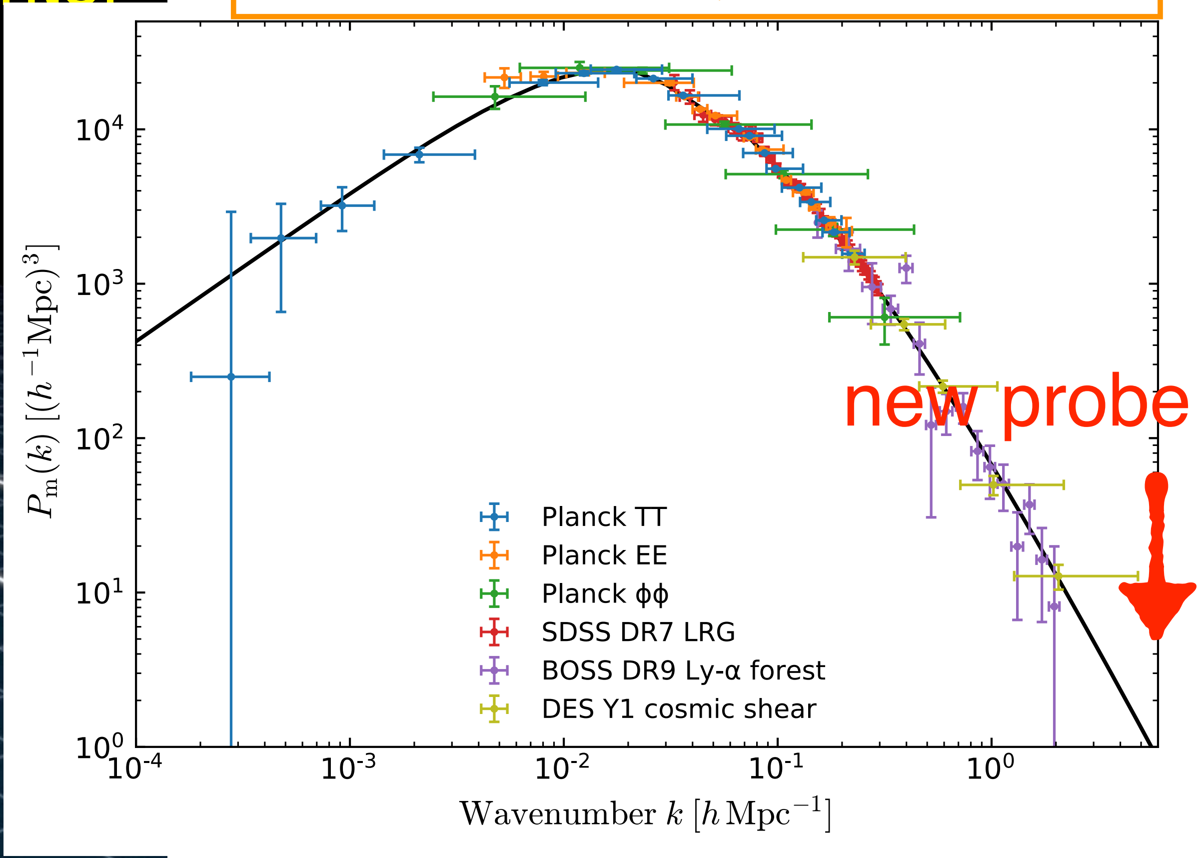
$$k \sim 100\, h/\mathrm{Mpc} \quad M \sim 10^6\, M_\odot/h$$

Chiba *et al.*, ApJ, 2005





Planck collaboration, arXiv:1807.06205



Strong-lens system

Constraints

- l.o.s. halos for 4 systems→ $m_{\rm WDM} \gtrsim 1.3\,{\rm keV}$ **Ionue, Takahashi, Takahashi, and Ishiyama, MNRAS, 2015**
- l.o.s. halos + substructures for 7 systems → $m_{\rm WDM} \gtrsim 5.6\,{\rm keV}$ **Gilman *et al.*, MNRAS, 2020**
- l.o.s. halos + substructures for 8 systems → $m_{\rm WDM} \gtrsim 5.2\,{\rm keV}$ **Hsueh *et al.*, MNRAS, 2020**

Constraints from Lyman-α forest

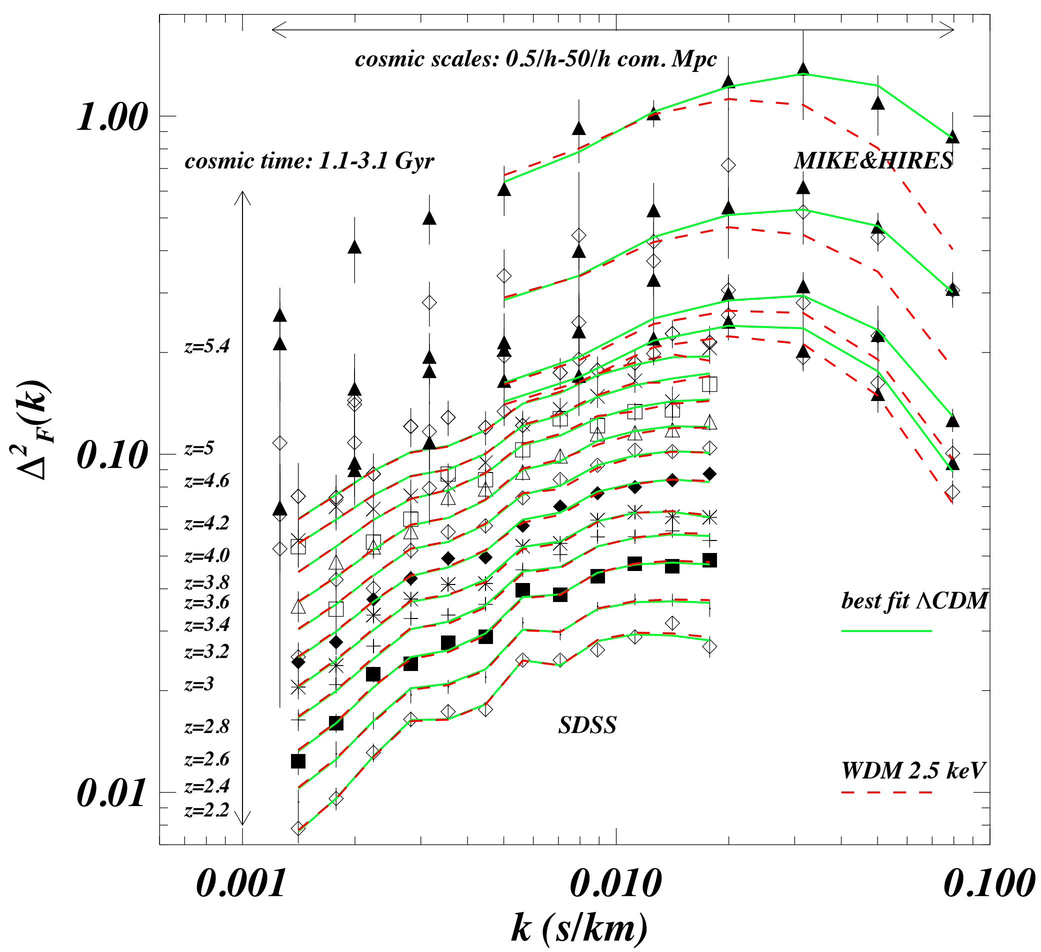
- probe clumping of neutral hydrogen

$m_{\rm WDM} \gtrsim 2.0\,{\rm keV}$ **Viel *et al.*, PRD, 2005**

$m_{\rm WDM} \gtrsim 3.3\,{\rm keV}$ **Baur *et al.*, JCAP, 2016**

$m_{\rm WDM} \gtrsim 4.09\,{\rm keV}$ **Viel, Becker, Bolton, and Haehnelt, PRD, 2013**

$m_{\rm WDM} \gtrsim 5.3\,{\rm keV}$ **Iršič, Viel *et al.*, PRD, 2017**



Short summary

WDM solution to the small-scale issues has been disfavored

$m_{\rm WDM} \sim 2\,{\rm keV}$ $m_{\rm WDM} \gtrsim 5\,{\rm keV}$

- may not be conclusive in light of systematics

How meaningful to place a constraint further?

Any viable alternative solving the small-scale issues?

Questions

WDM solution to the small-scale issues has been disfavored

How meaningful to place a constraint further?

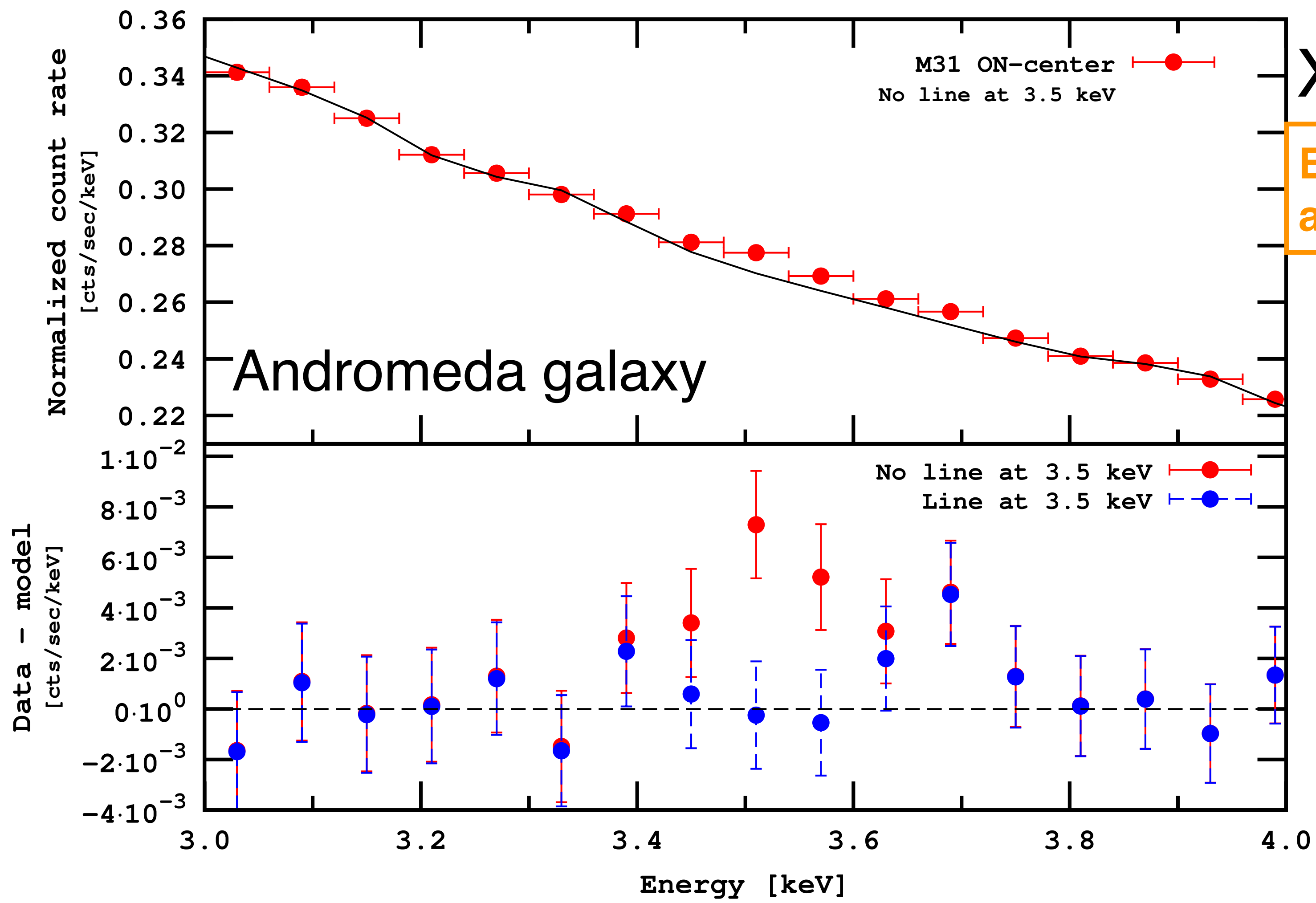
- small-scale issues are one of the motivations of light dark matter but not all

Any viable alternative solving the small-scale issues?

X-ray line excess

3.5 keV line excess is reported

- in some instruments, but not in others; in some objects, but not in others



XMM-Newton excess

Boyarsky, Ruchayskiy, Iakubovskyi, and Franse, PRL, 2014

- continuum (w/ instrumental)
- +3.5 keV line

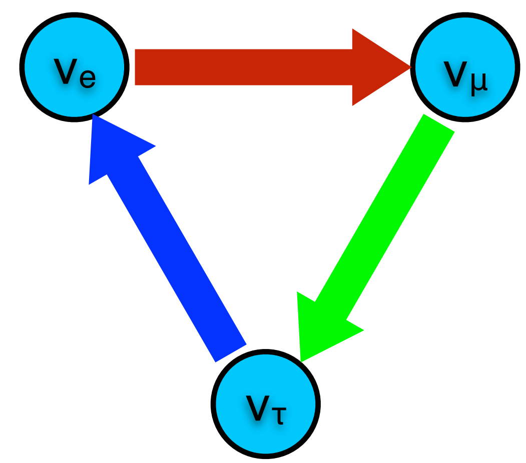
Chandra no excess for Andromeda galaxy

Horiuchi *et al.*, PRD, 2014

X-ray line excess

3.5 keV line excess may originate from 7 keV dark matter decay

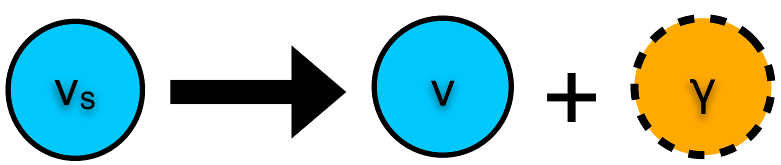
- structure formation constraints are relevant $m_{\rm WDM} \sim 2\,{\rm keV}$



Sterile neutrino

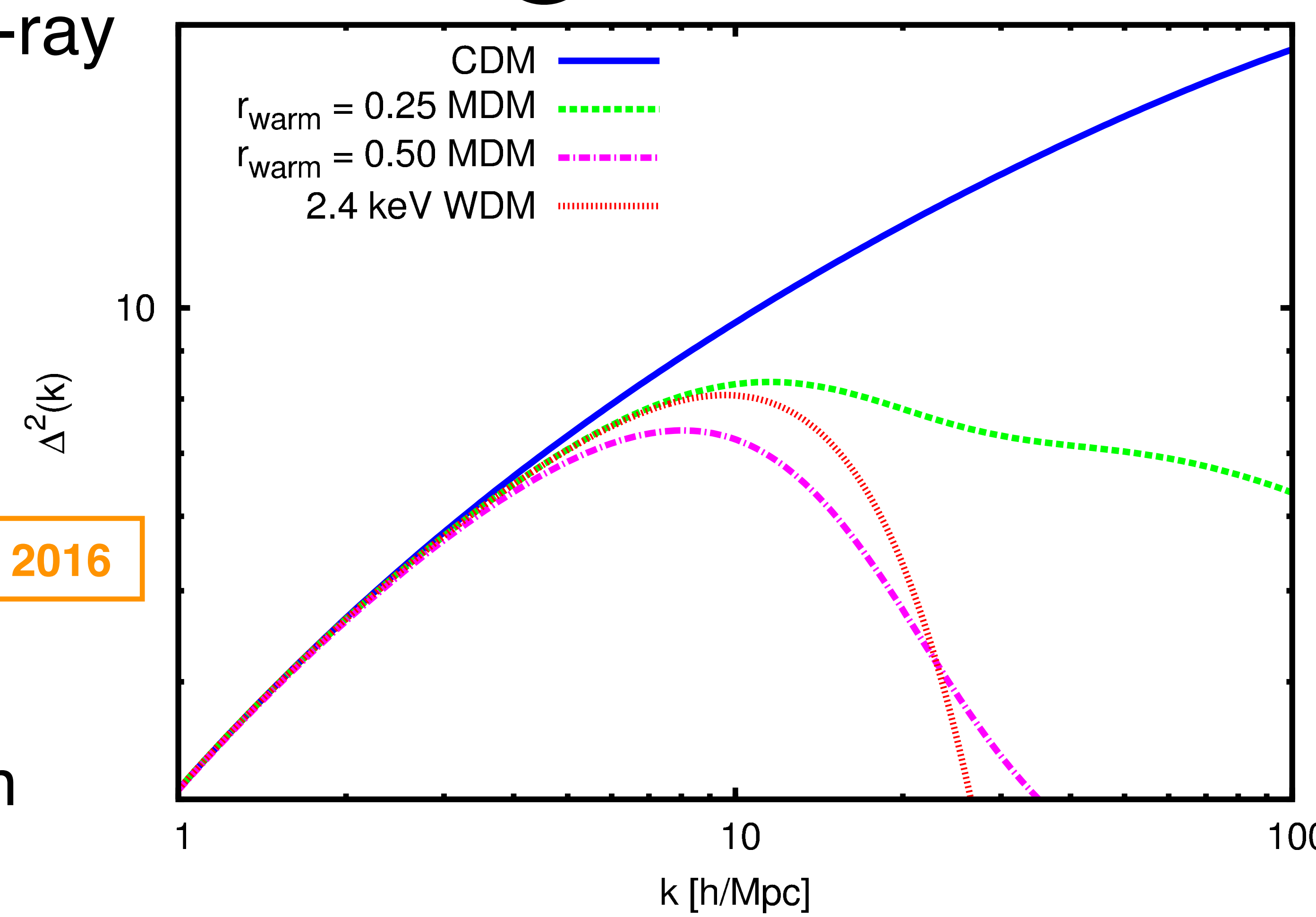
- motivated by the neutrino oscillation

- decay into active neutrino + X-ray



- accounts for 20-60% of DM mass density

Harada and AK, JCAP, 2016



- to explain the 3.5 keV line

- Dodelson-Widrow production

Strong-lens system

Constraint

- l.o.s. halos for 4 systems

AK, Inoue, and Takahashi, PRD, 2016

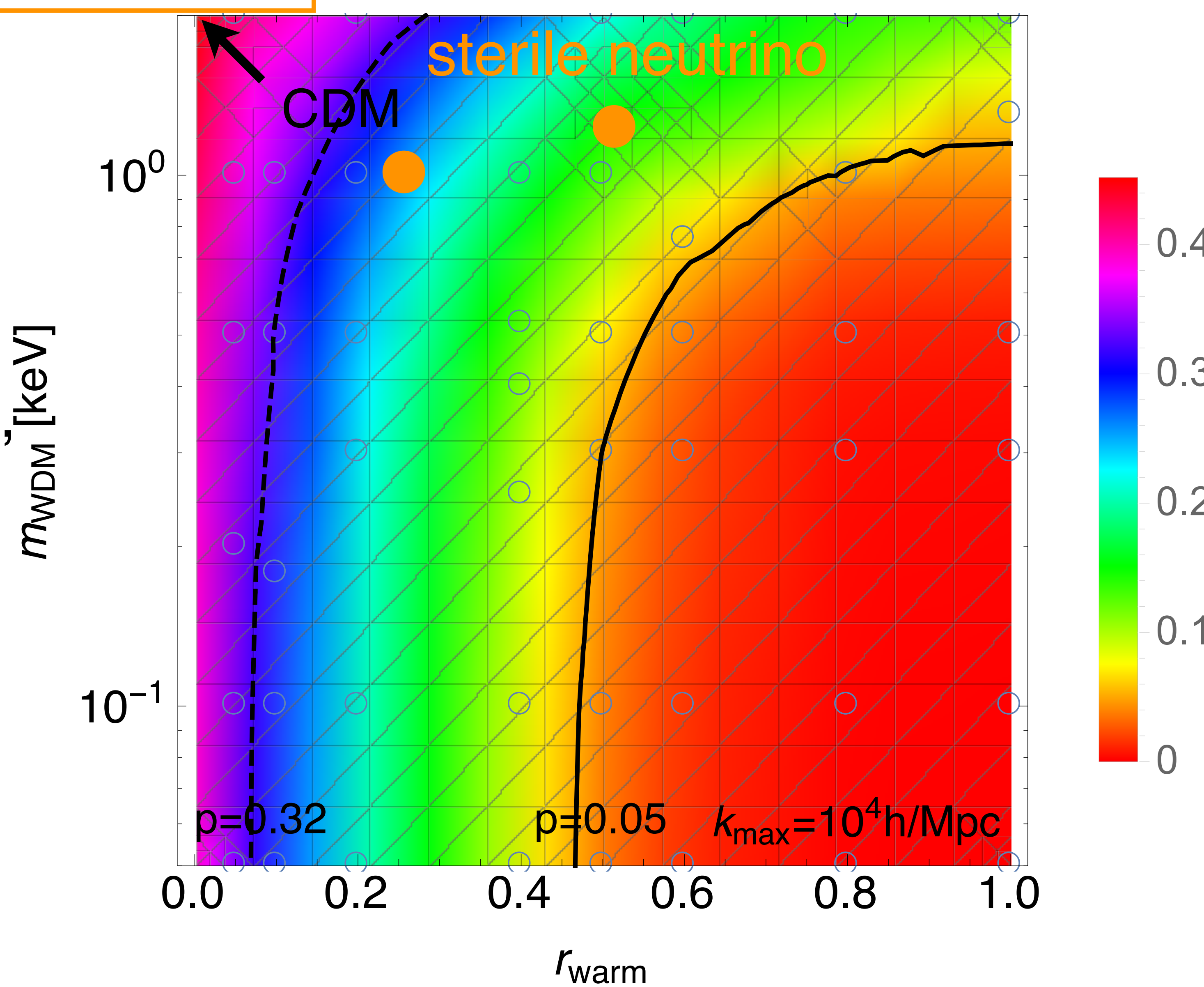
$$m_{\rm WDM} \gtrsim 1.3\,{\rm keV}$$

Ionue, Takahashi, Takahashi, and Ishiyama, MNRAS, 2015

- mapping $m_s = 7\,{\rm keV} \rightarrow m_{\rm WDM}$

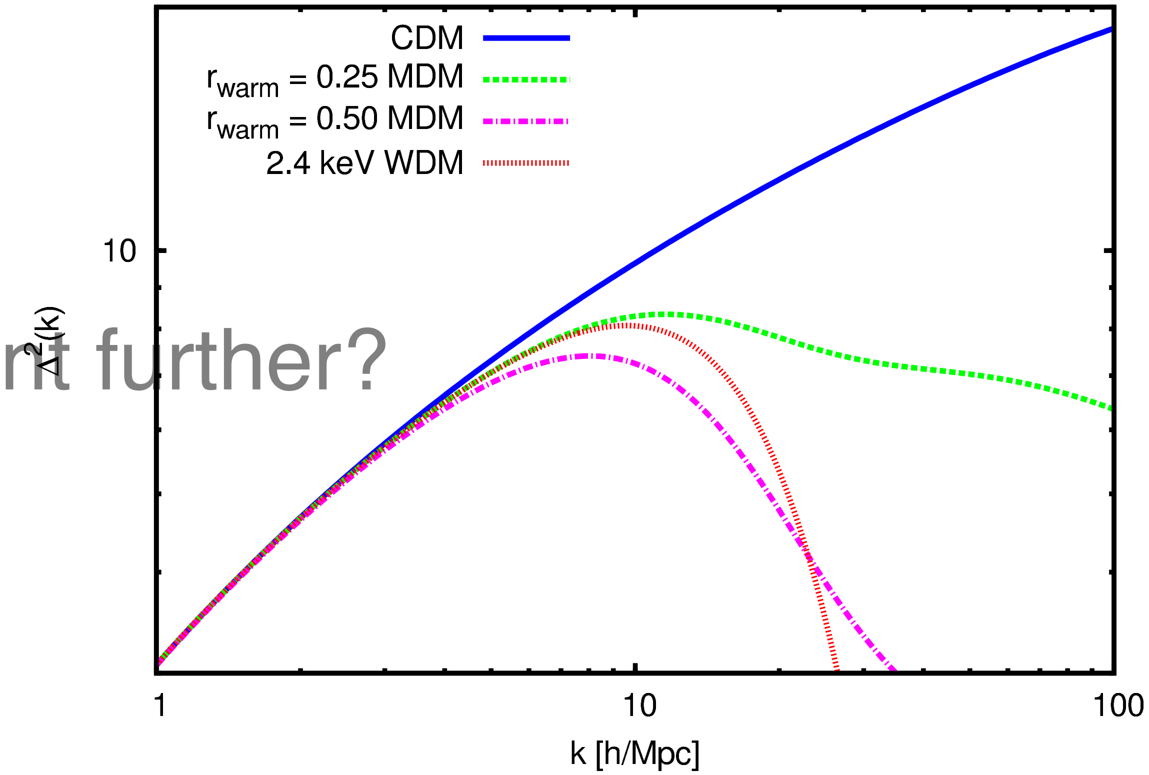
AK and Yanagi, JCAP, 2019

- sterile neutrino (partial) WDM, motivated by the 3.5 keV line, is viable at 2σ



Questions

WDM solution to the small-scale issues has been disfavored



How meaningful to place a constraint further?

Any viable alternative solving the small-scale issues?

- WDM is more different from CDM at higher z
  - non-linear growth
- any DM similar to CDM at higher z?

strong-lens systems $z \sim 1$

Lyman- α forest $z \sim 3$

Alternative to WDM

Decaying dark matter (DDM) **Peter, PRD, 2010**

0 → 1 + 2 $\Gamma^{-1} \sim 10\,\mathrm{Gyr}$ - lifetime V_k - kick velocity

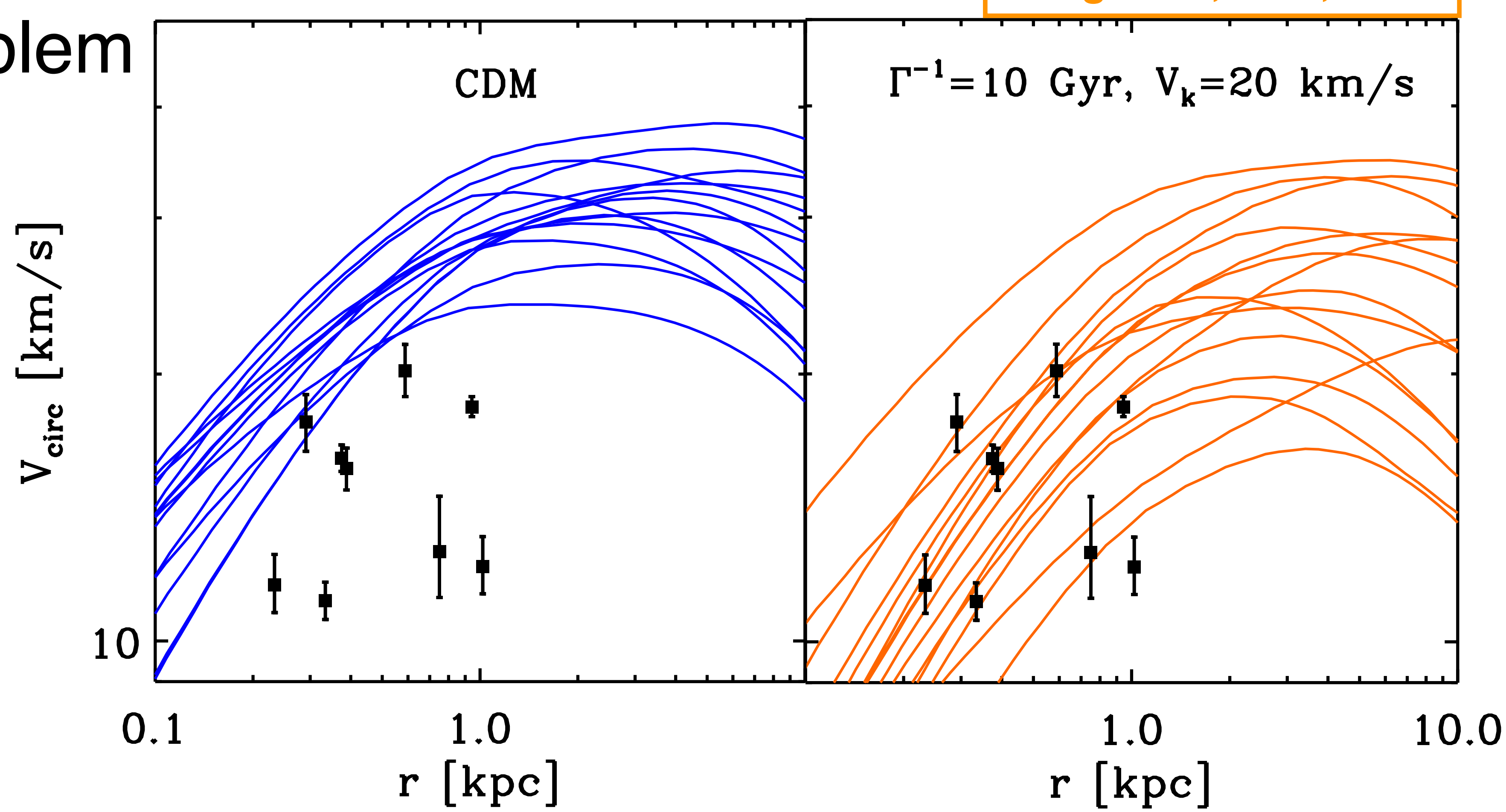
- CDM before decay

- motivated by SUSY axion models **Bae, AK, and Kim, PRD, 2019**

axino → axion + gravitino

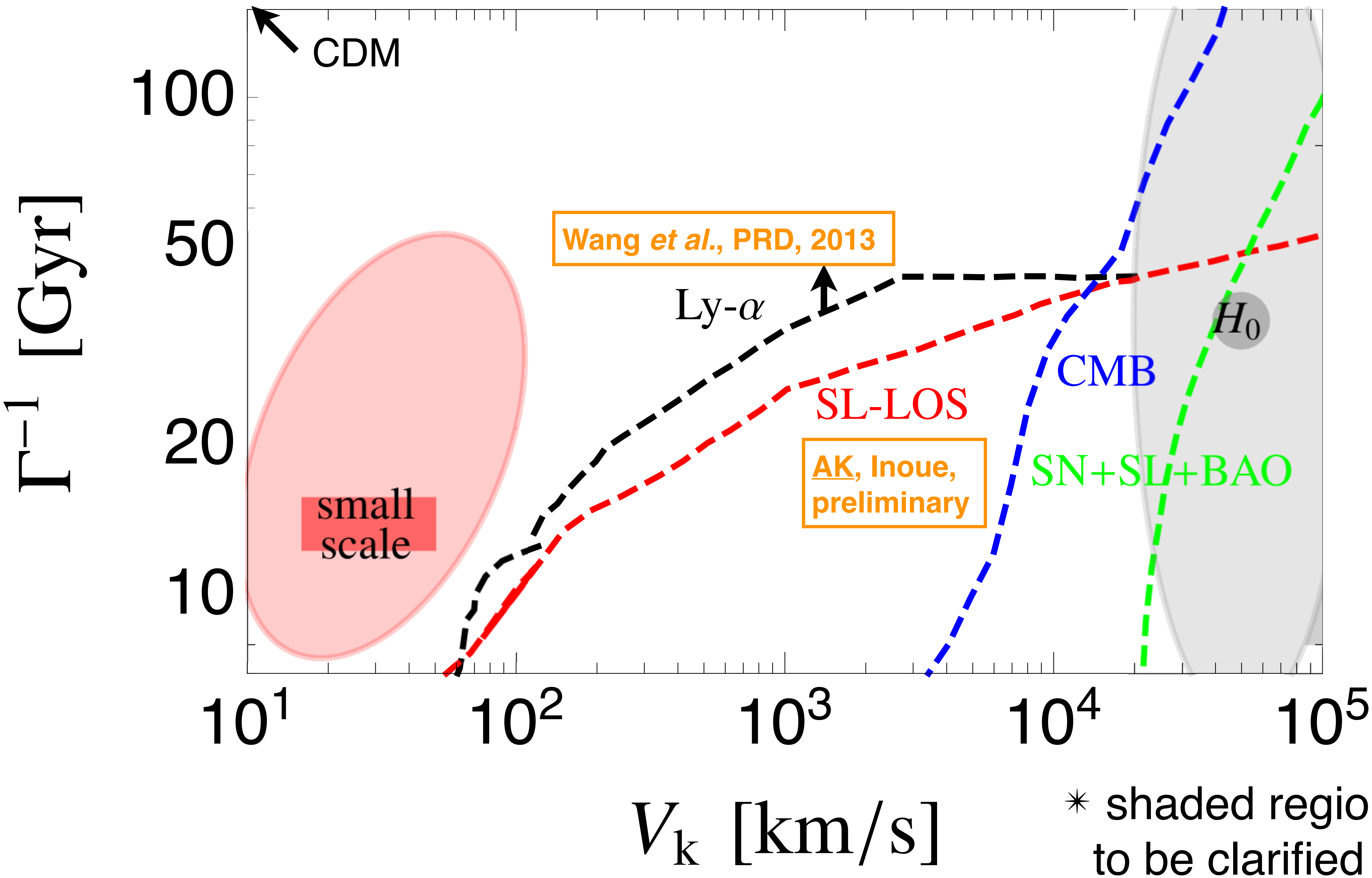
Too-big-to-fail problem

Wang *et al.*, PRD, 2014



DDM parameter space

DDM solution to small-scale issues may be consistent w/ strong-lens systems and Lyman- α forest



✳ shaded regions are to be clarified further

Summary

WDM solution to the small-scale issues has been disfavored

$m_{\mathrm{WDM}} \sim 2\,\mathrm{keV}$ $m_{\mathrm{WDM}} \gtrsim 5\,\mathrm{keV}$

- may not be conclusive in light of systematics

How meaningful to place a constraint further?

- light dark matter is particle-physics motivated (e.g., neutrino oscillation → sterile neutrino)

- important to cross-check dark matter interpretation of other signals (e.g., X-ray line)

Any viable alternative solving the small-scale issues?

- DDM is similar to CDM before decay

$\Gamma^{-1} \sim 10\,\mathrm{Gyr}$

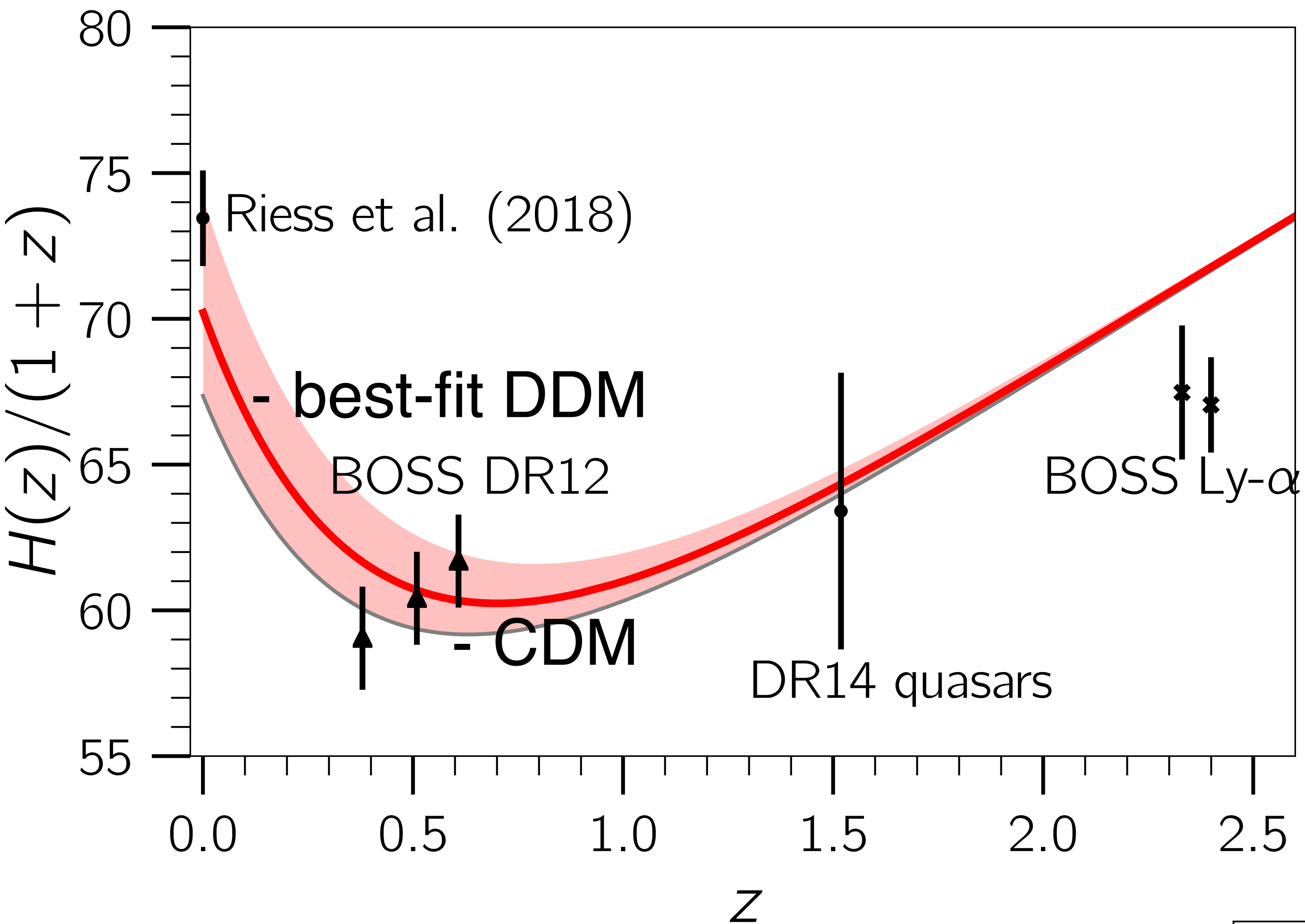
strong-lens systems

$z \sim 1$

Lyman- α forest

$z \sim 3$

Hubble parameter

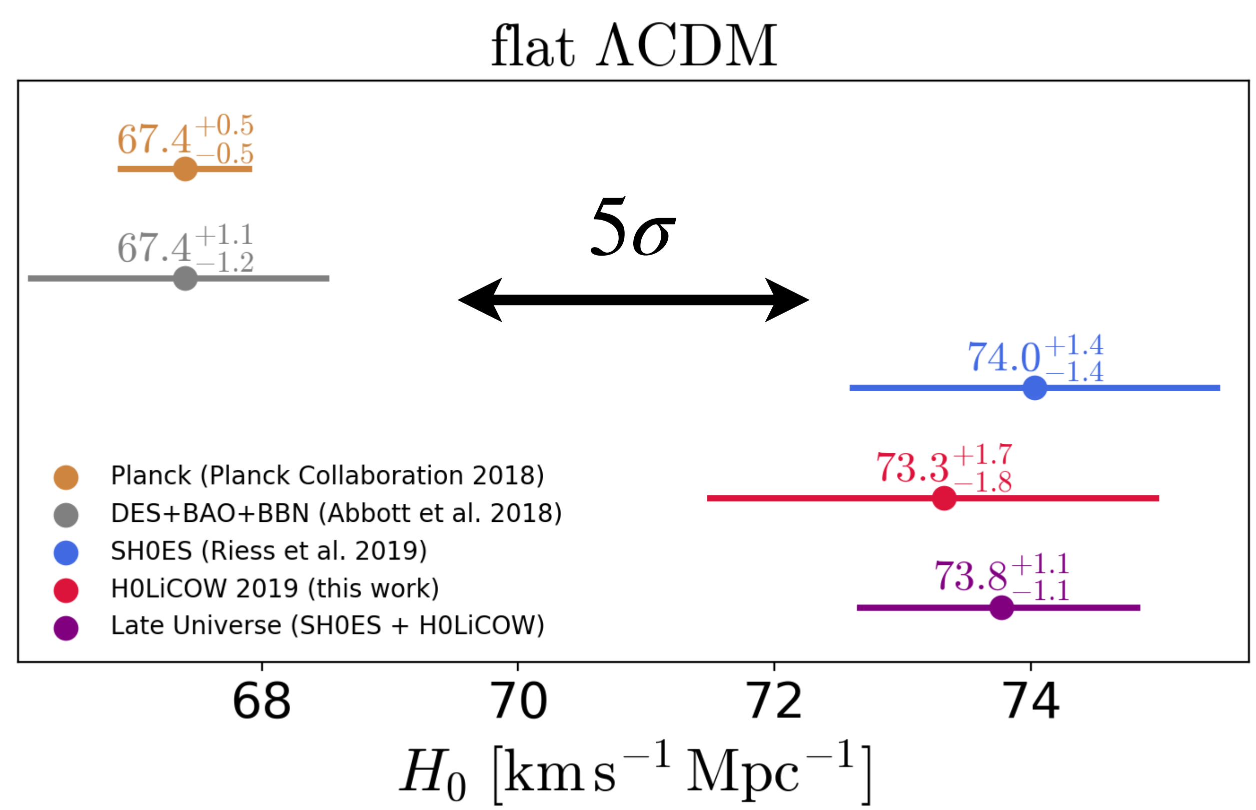


MCMC for low-redshift data

Vattis, Koushiappas, and Loeb, PRD, 2019

$\log_{10} V_k/c$	$\log_{10}(\Gamma^{-1}/\mathrm{Gyr})$
$-0.70^{+0.17}_{-2.18}$	$1.55^{+0.63}_{-0.25}$

H0LiCOW collaboration, MNRAS, 2020



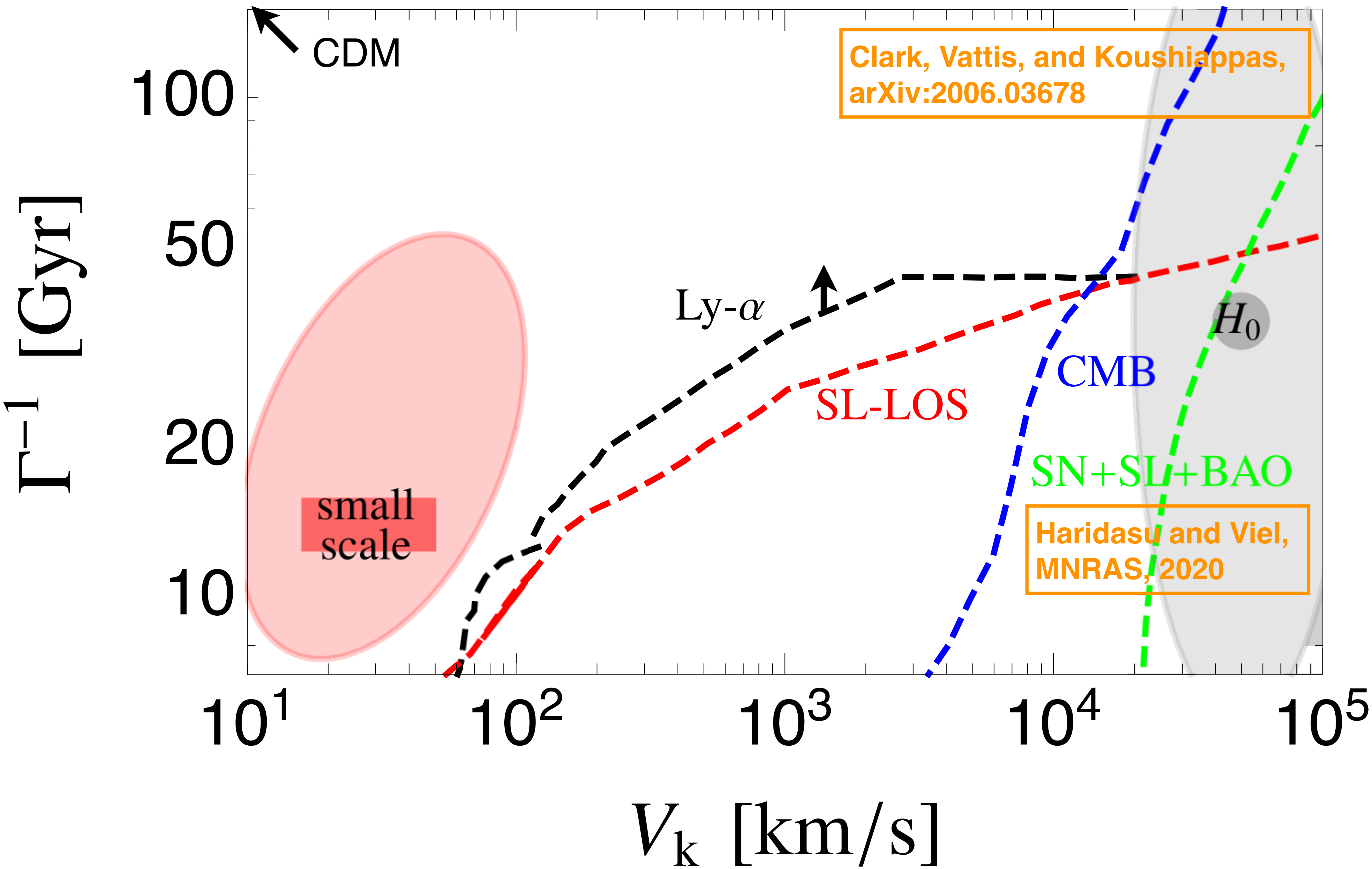
Other parameters are fixed to be Planck values

- self-consistent analysis required

$100\theta_*$ or $D_A(z_*)$ changed

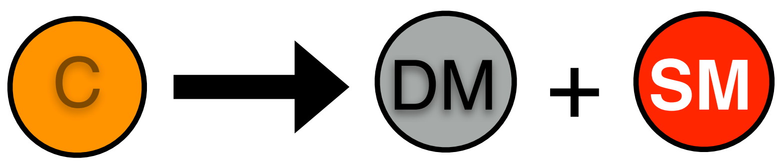
DDM parameter space

Recent analyses argues that a DDM solution to H_0 is not significantly preferred to CDM

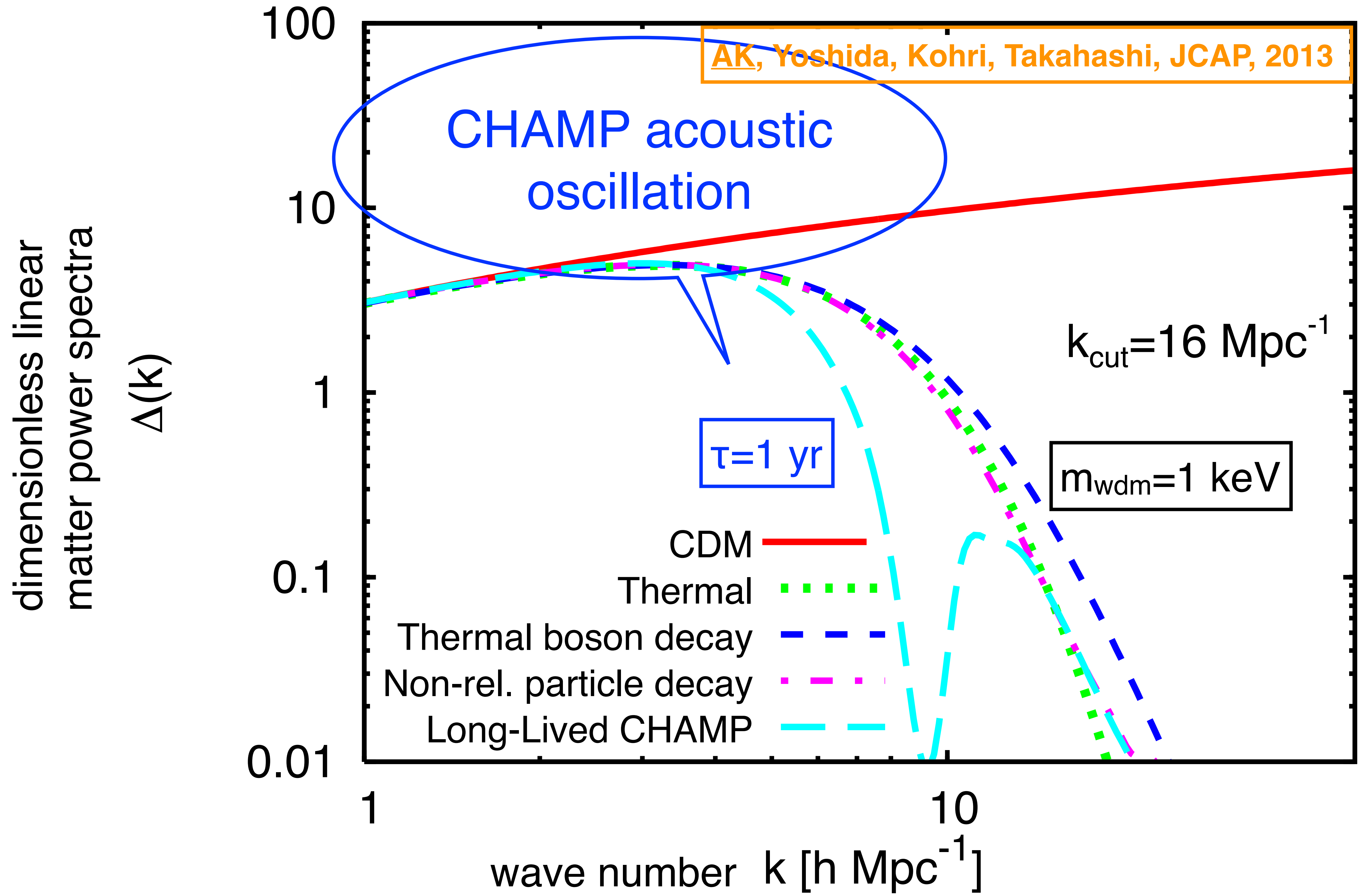


Thank you for your attention

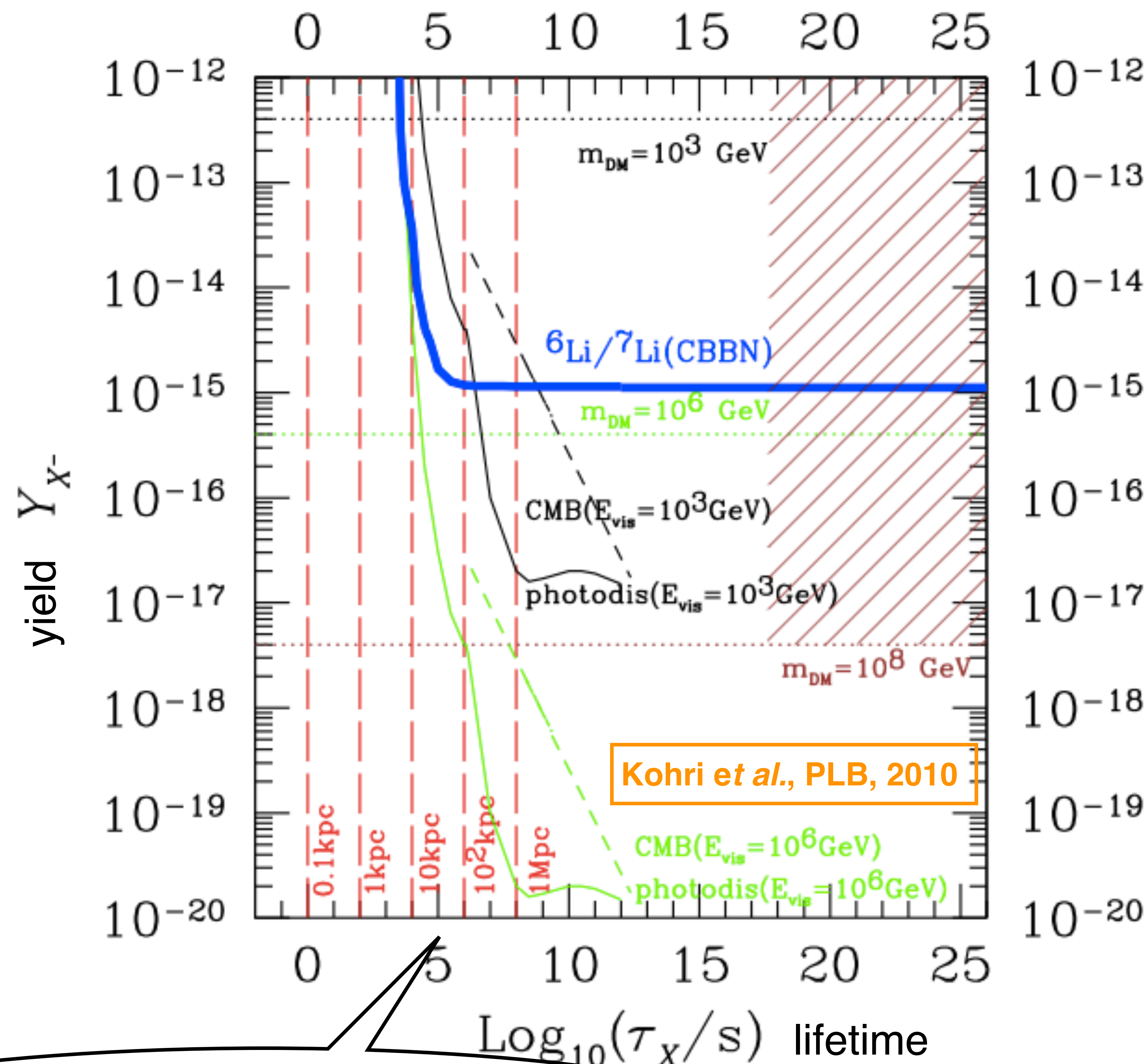
Long-lived Charged massive particle



Plasma (γ e- p+) pressure prevents CHAMPs from falling into the bottom of gravitational potential

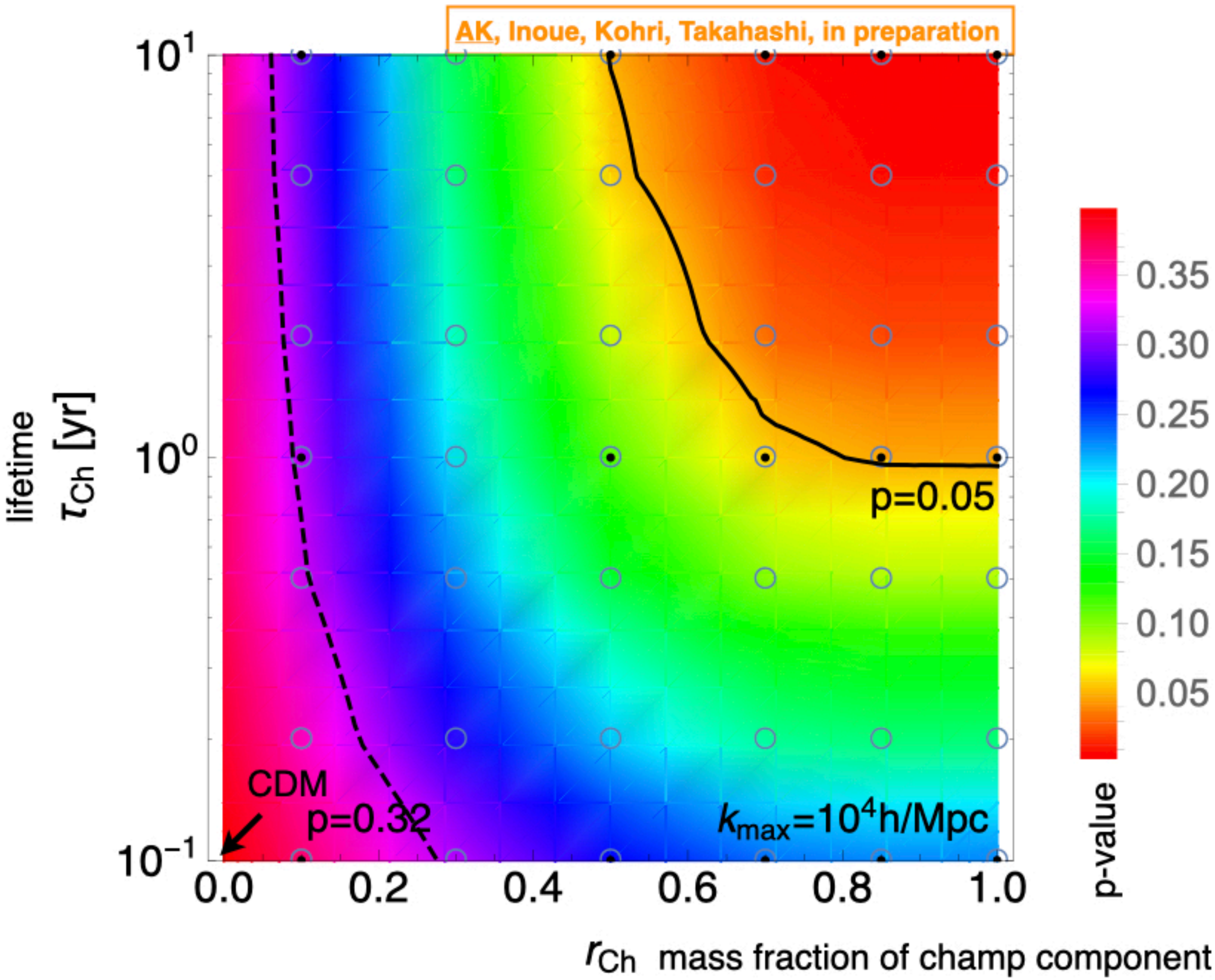


CHAMP parameter space



cutoff in matter power around the subgalactic scale

Likelihood


AK, Inoue, Kohri, Takahashi, in preparation
10^{1}
10^{0}
10^{-1}
lifetime
τ_{Ch} [yr]
p=0.05
CDM
p=0.32
$k_{max}=10^{4}$h/Mpc
0.0
0.2
0.4
0.6
0.8
1.0
r_{Ch} mass fraction of champ component
0.35
0.30
0.25
0.20
0.15
0.10
0.05
p-value

Linear matter power spectrum

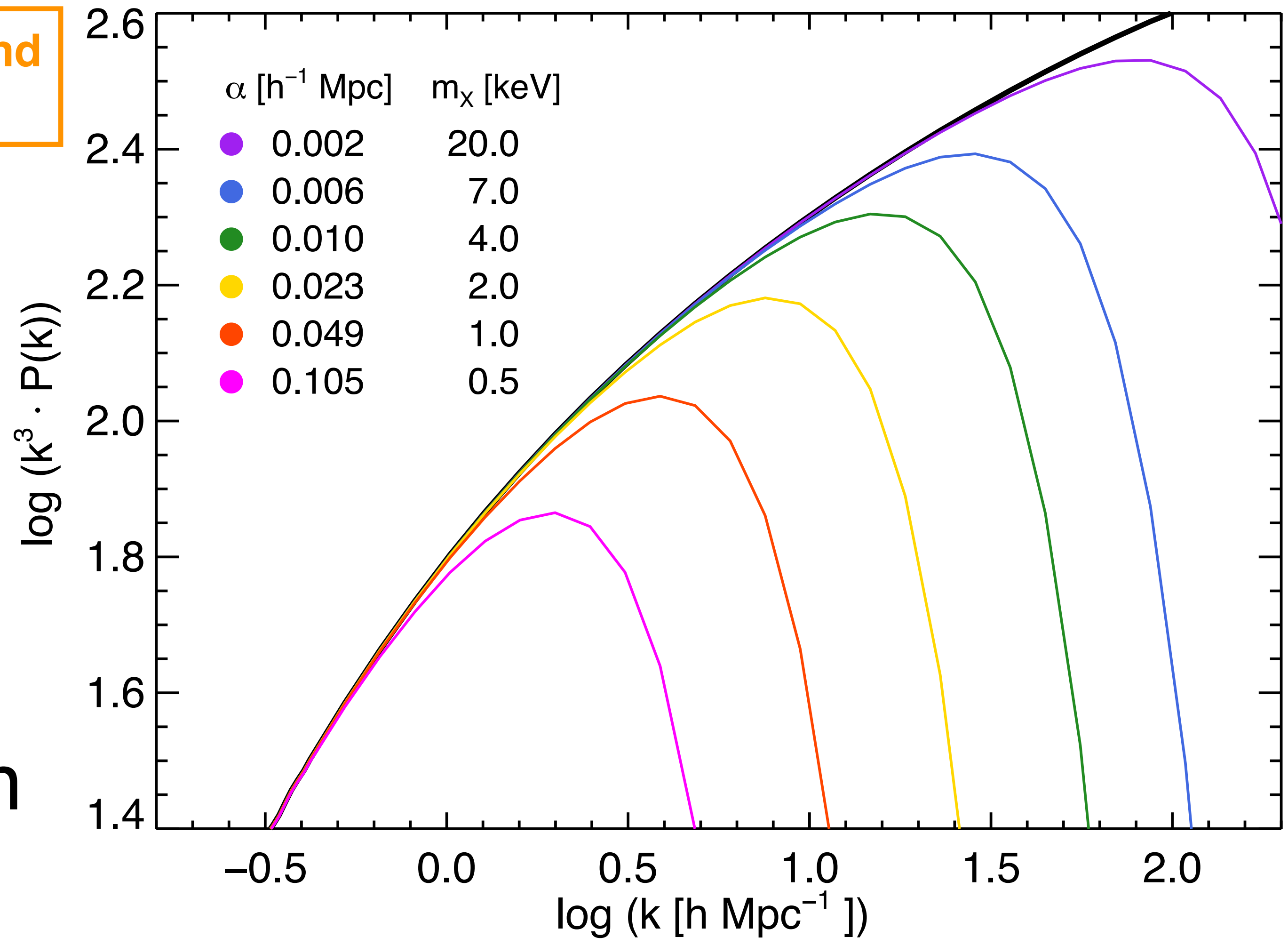
m_{WDM} parametrizes the linear matter power spectrum:

Viel, Lesgourgues, Haehnelt, Matarrese, and Riotto, PRD, 2005

$$P_{\text{WDM}}/P_{\text{CDM}} = T^2_{\text{WDM}}(k) = \left[1 + (\alpha k)^{2\nu}\right]^{-10/\nu} \qquad \nu = 1.12$$

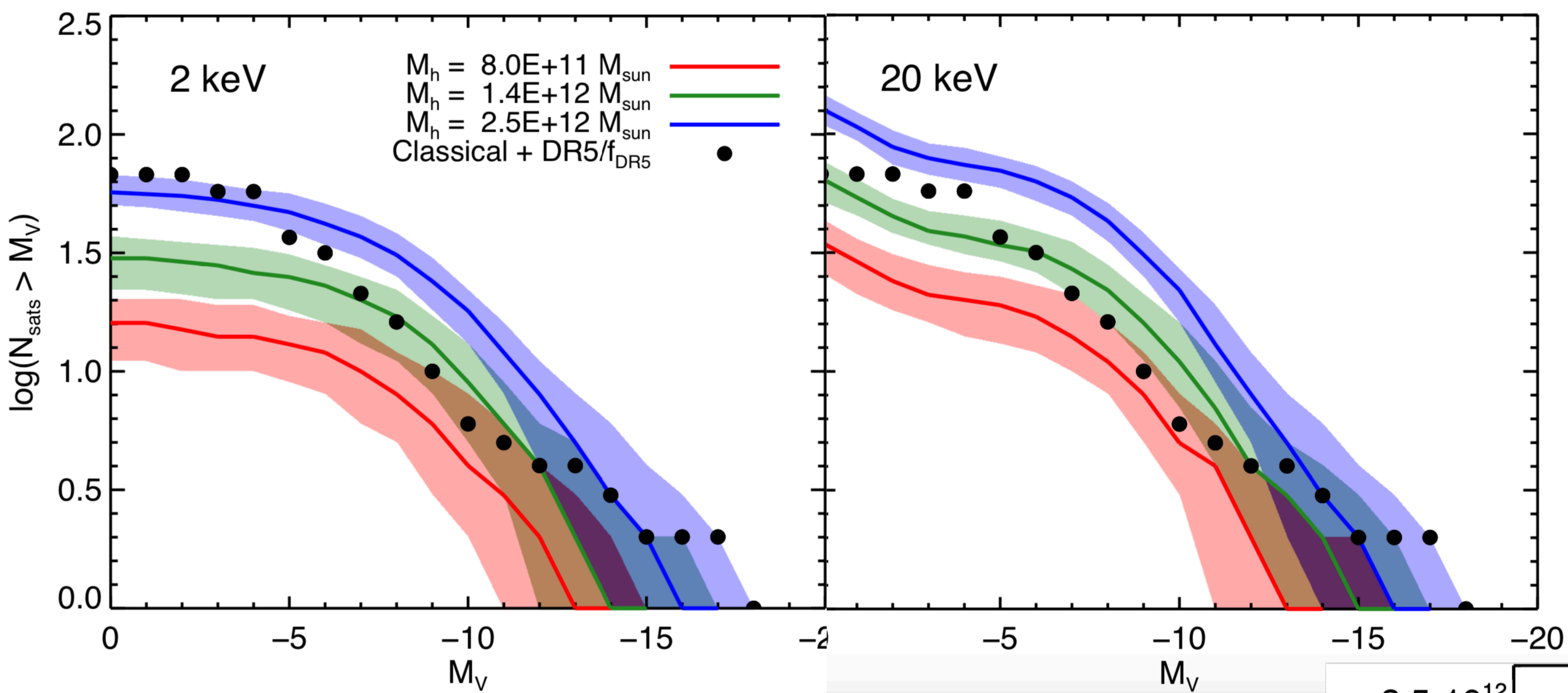
$$\alpha = 0.049\,\text{Mpc}/h \left(\frac{m_{\text{WDM}}}{\text{keV}}\right)^{-1.11} \left(\frac{\Omega_{\text{WDM}}}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22}$$

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



WDM provides less seed for small-scale structure formation

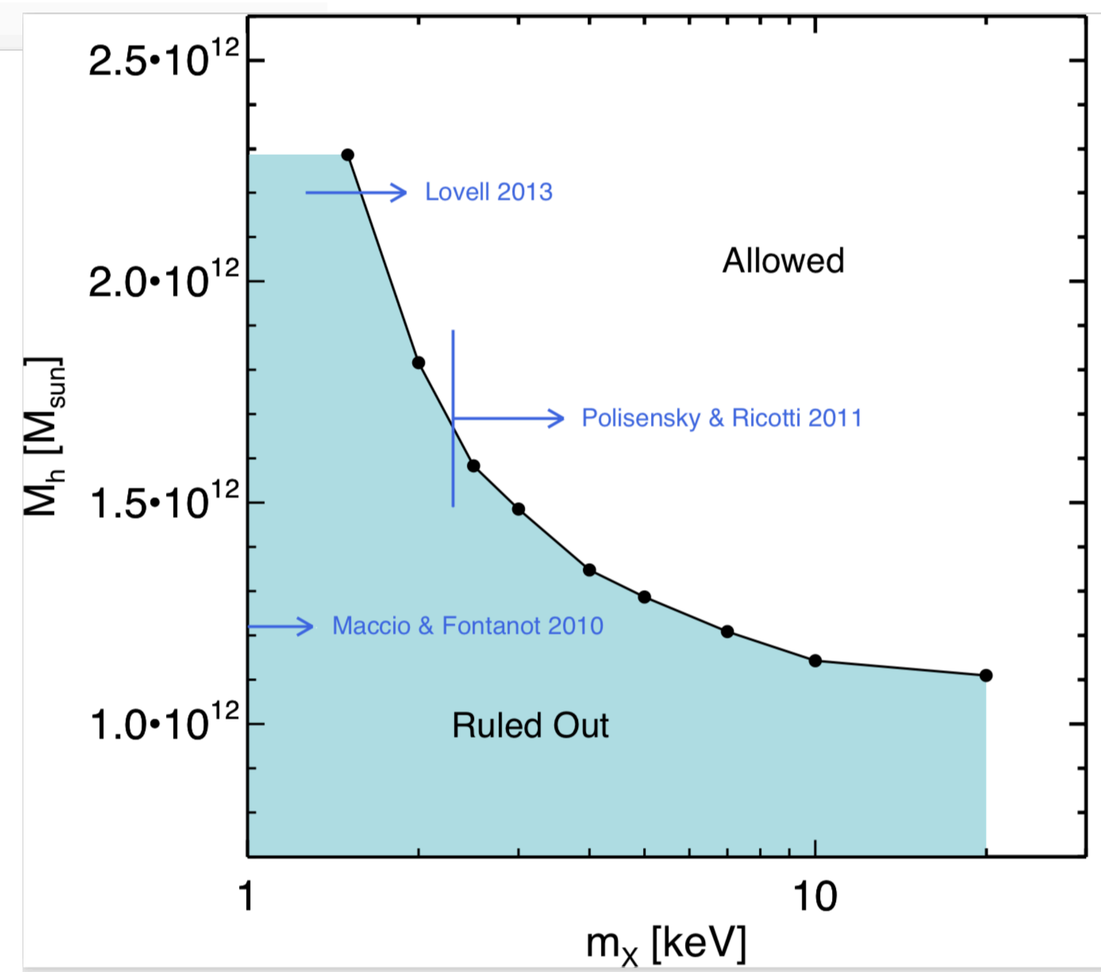
Missing satellite problem w/ WDM



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

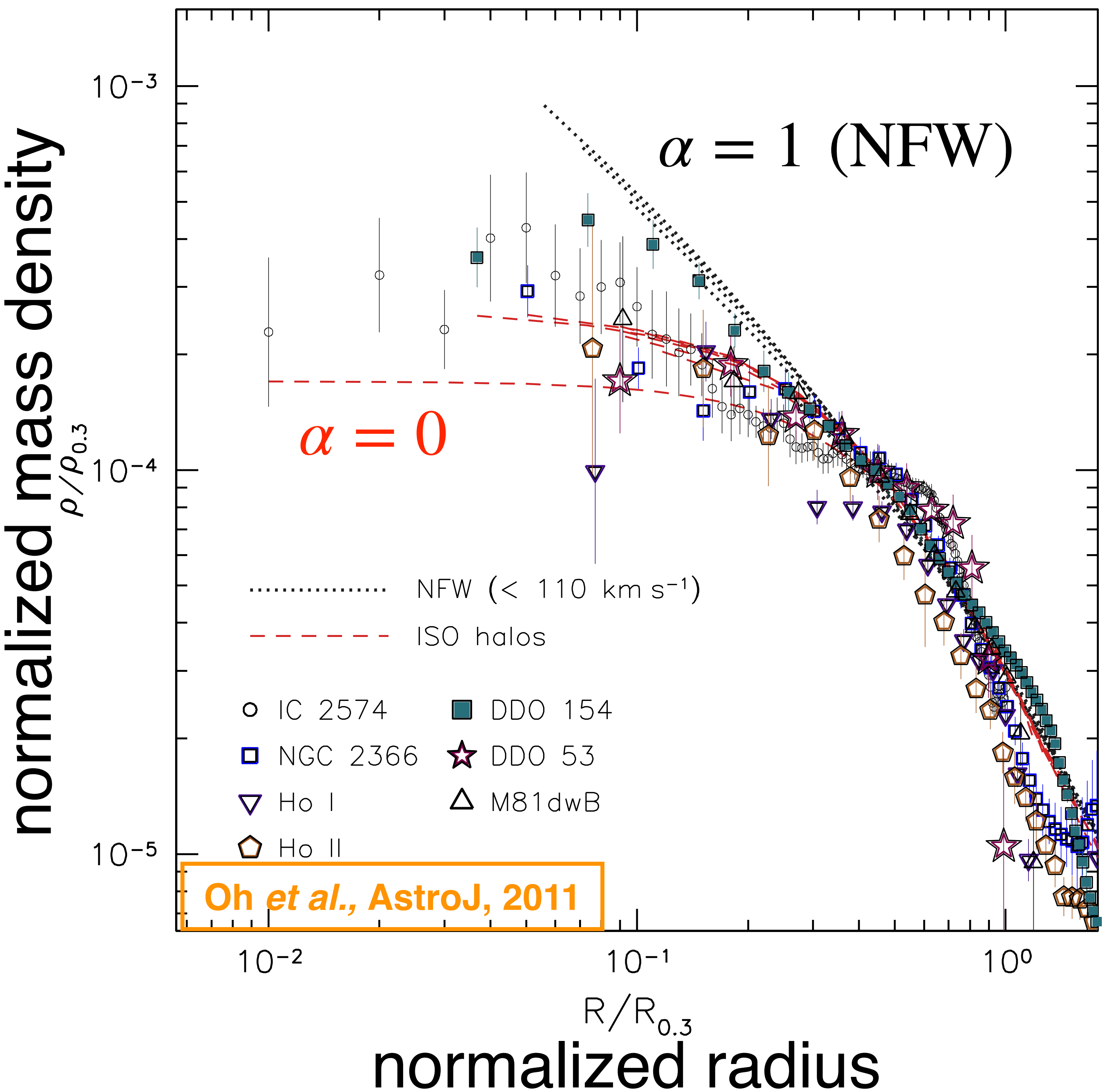
WDM reduces a predicted number of satellite galaxies

Should not go below the observed number
$\rightarrow m_{\mathrm{WDM}} \gtrsim 2\,\mathrm{keV}$



Cusp vs core problem

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



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

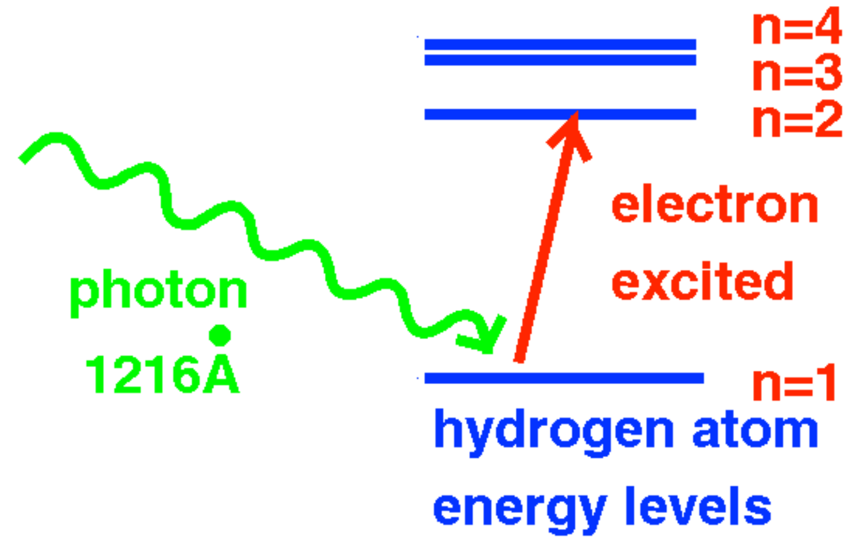
Observations infer cored profile in the inner region rather than cuspy NFW profile

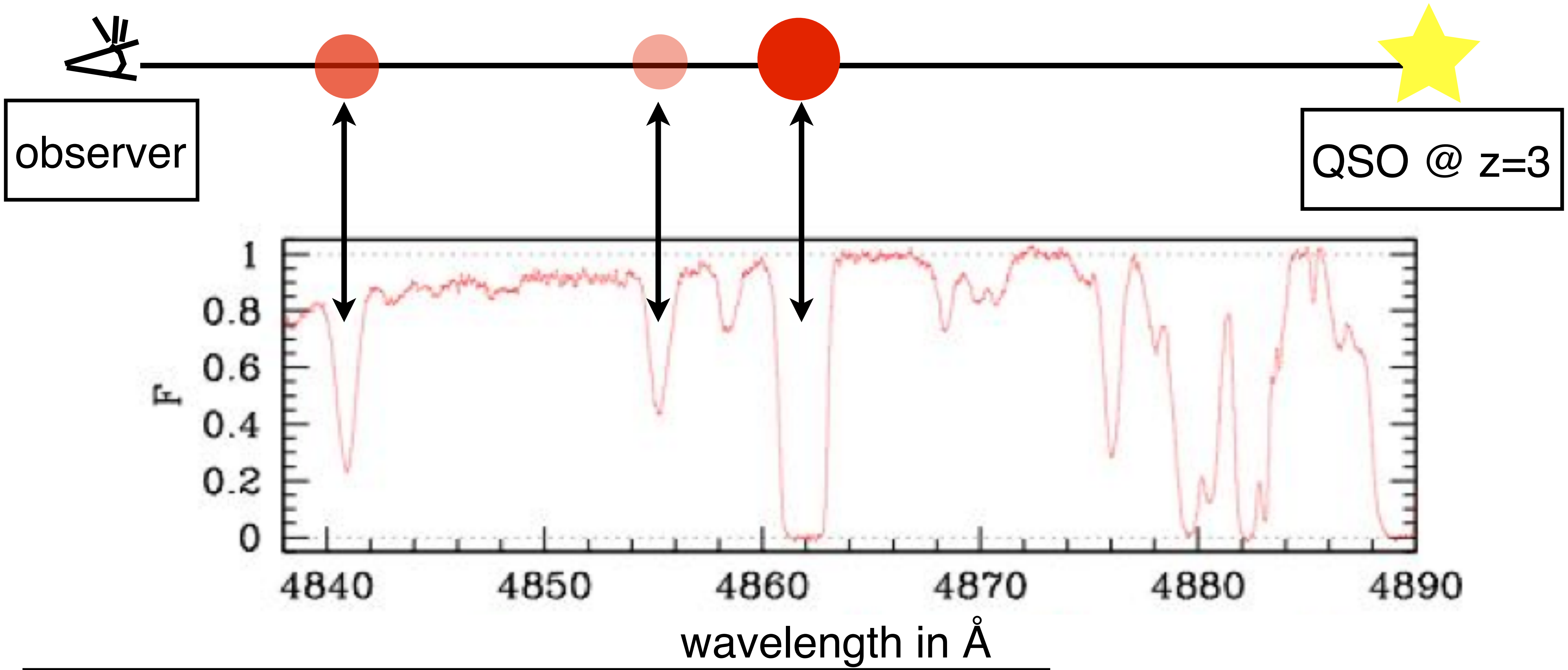
inner profile: $\rho_{\rm DM} \propto r^{-\alpha}$

- field dwarf spheroidal galaxies $\sim 10^9\, M_\odot$

Lyman-alpha forest as a probe of matter distribution

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





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

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

FIMP ≠ thermal WDM

One cannot conclude that 7 keV FIMP DM (for 3.5 keV line) is cold enough from $m_{\rm WDM} \gtrsim 3.3\,{\rm keV}$

Thermal WDM: entropy conservation after decoupling

$$T_{\rm DM} = \left(\frac{g_*(T)}{g_*(T_{\rm dec})}\right)^{1/3} T$$

$$\Omega_{\rm WDM} h^2 = \left(\frac{m_{\rm WDM}}{94\,{\rm eV}}\right)\left(\frac{T_{\rm WDM}}{T_\nu}\right)^3 = 7.5\left(\frac{m_{\rm WDM}}{7\,{\rm keV}}\right)\left(\frac{106.75}{g_*(T_{\rm dec})}\right)$$

- extra entropy production (~100) after decoupling is needed to realize keV-scale WDM

Thermal WDM is much colder than naively expected
→ lower bound on the FIMP mass w/o entropy production is higher

Warmness

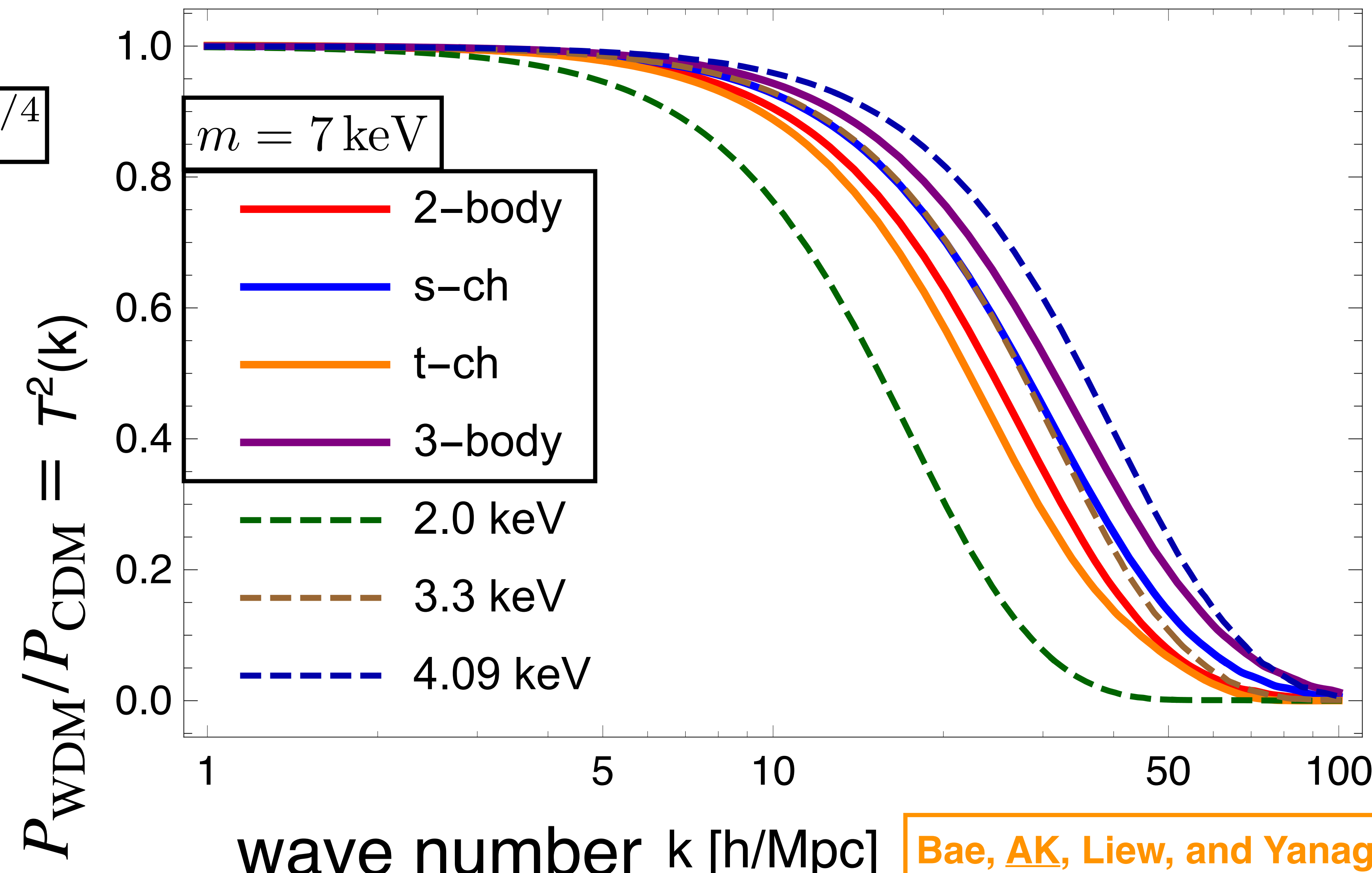
Quantity characterize warmness of DM:

$$\sigma^2 = \frac{T_{\rm DM}^2}{m^2}\tilde{\sigma}^2, \quad \tilde{\sigma}^2 = \frac{\int dq q^4 f(q)}{\int dq q^2 f(q)} \rightarrow m = 7\,{\rm keV}\left(\frac{m_{\rm WDM}}{2.5\,{\rm keV}(\tilde{\sigma}/3.6)^{-3/4}}\right)^{4/3}$$

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

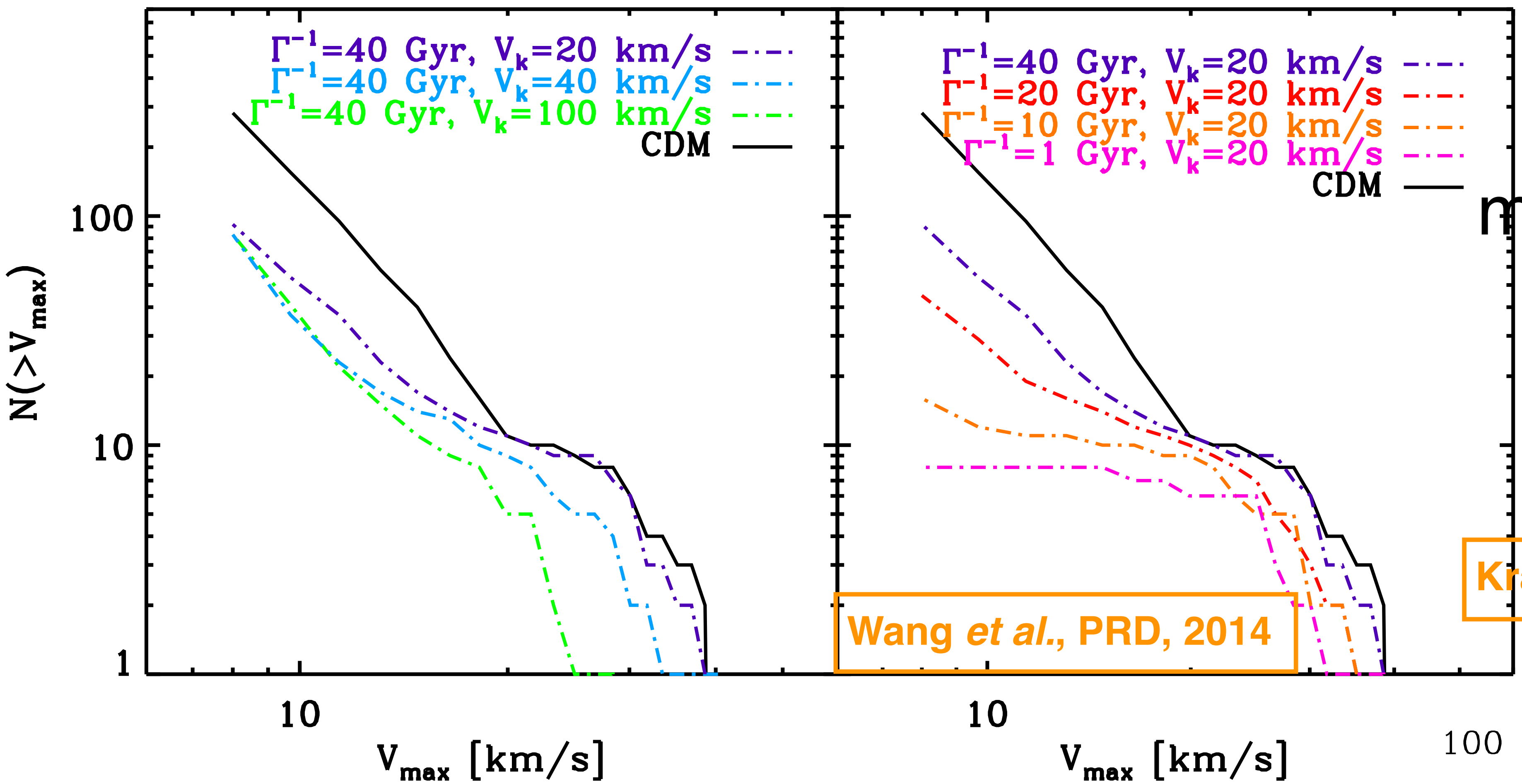
$$g_*(T_{\rm dec}) = 106.75$$

$2.5\,{\rm keV}(\tilde{\sigma}/3.6)^{-3/4}$
$= 2.9\,{\rm keV}$
$= 3.2\,{\rm keV}$
$= 2.7\,{\rm keV}$
$= 3.6\,{\rm keV}$



Bae, AK, Liew, and Yanagi, JCAP, 2017

MW satellites

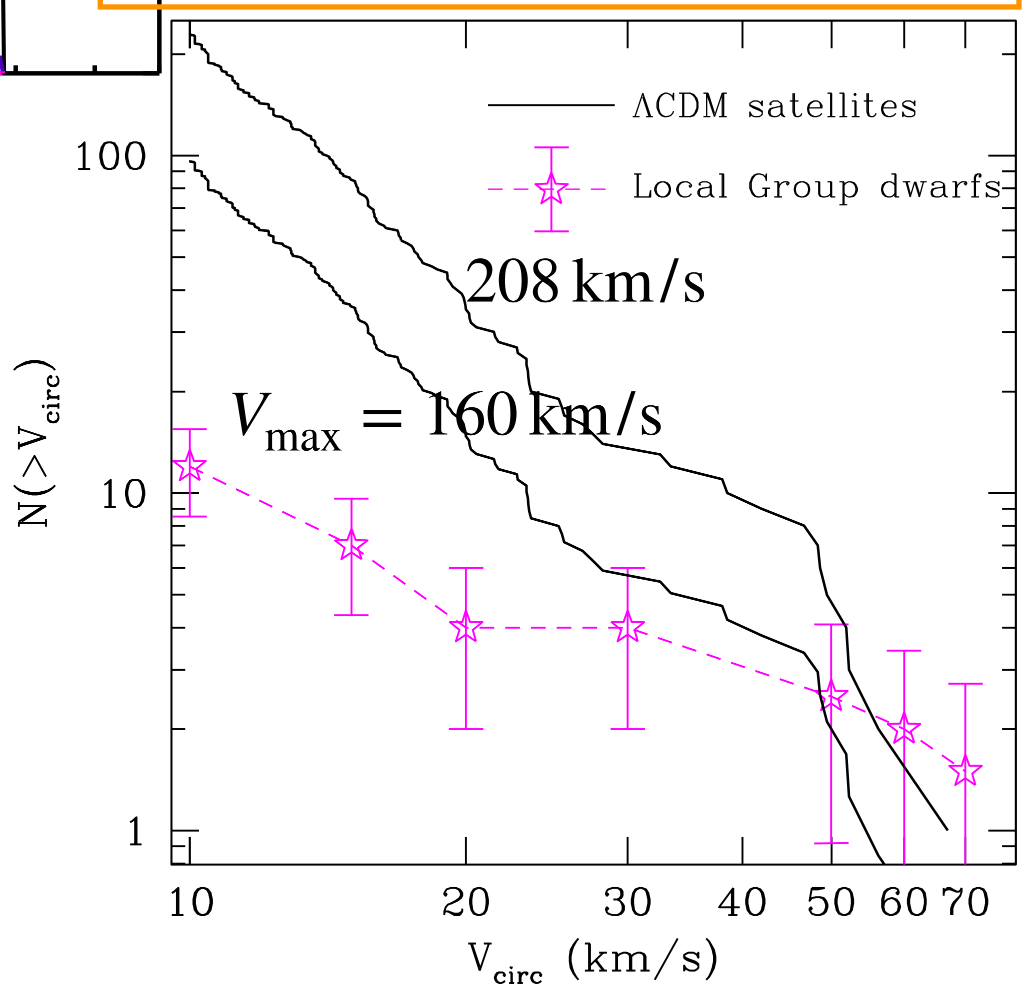


Wang *et al.*, PRD, 2014

missing satellite problem

- $\mathcal{O}(10)$ more subhalos than MW satellites

Kratsov, Advances in Astronomy, 2010

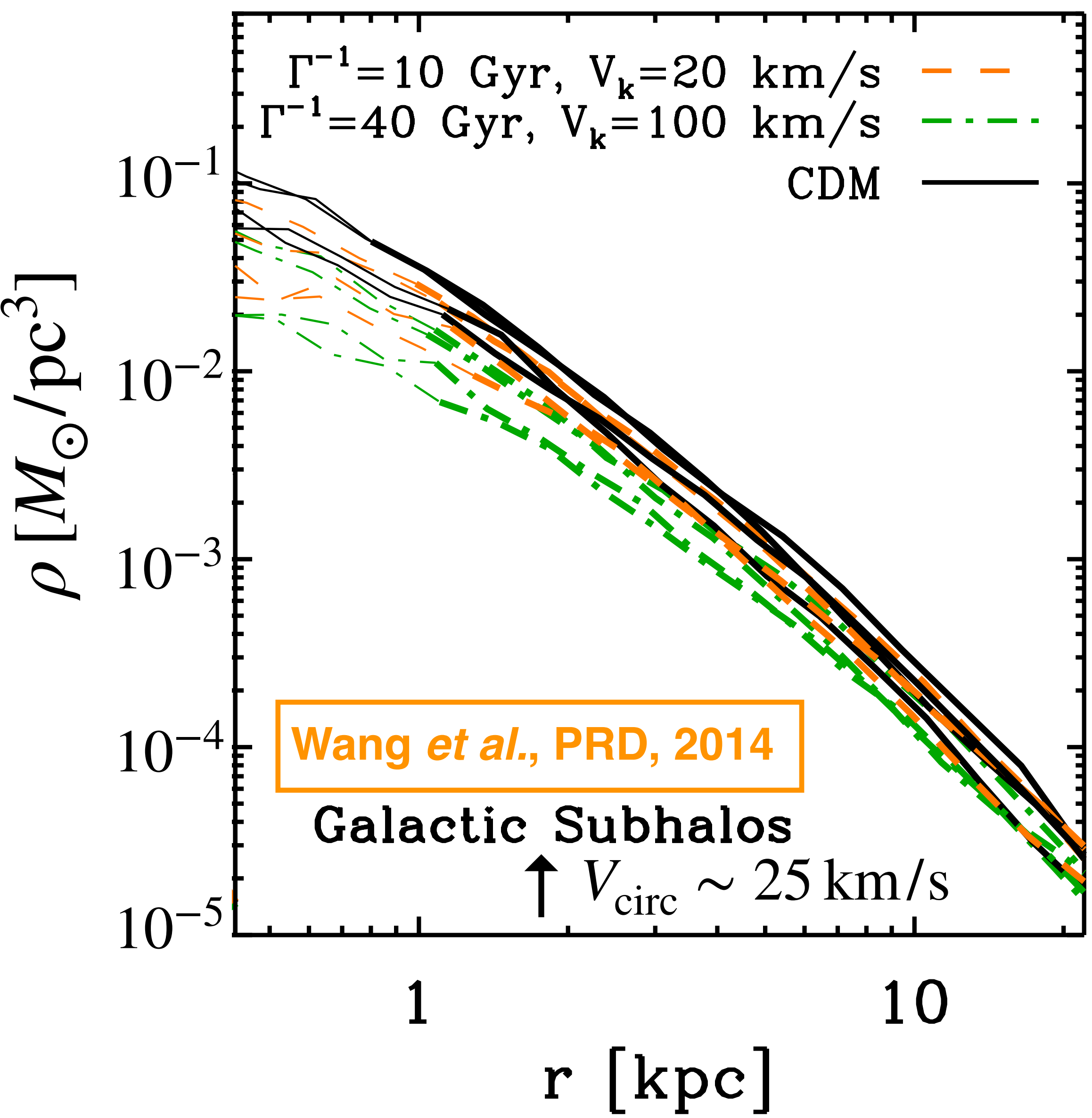


V_k vs V_{max}

For $V_k > V_{max}$, number of subhalos is almost insensitive to V_k

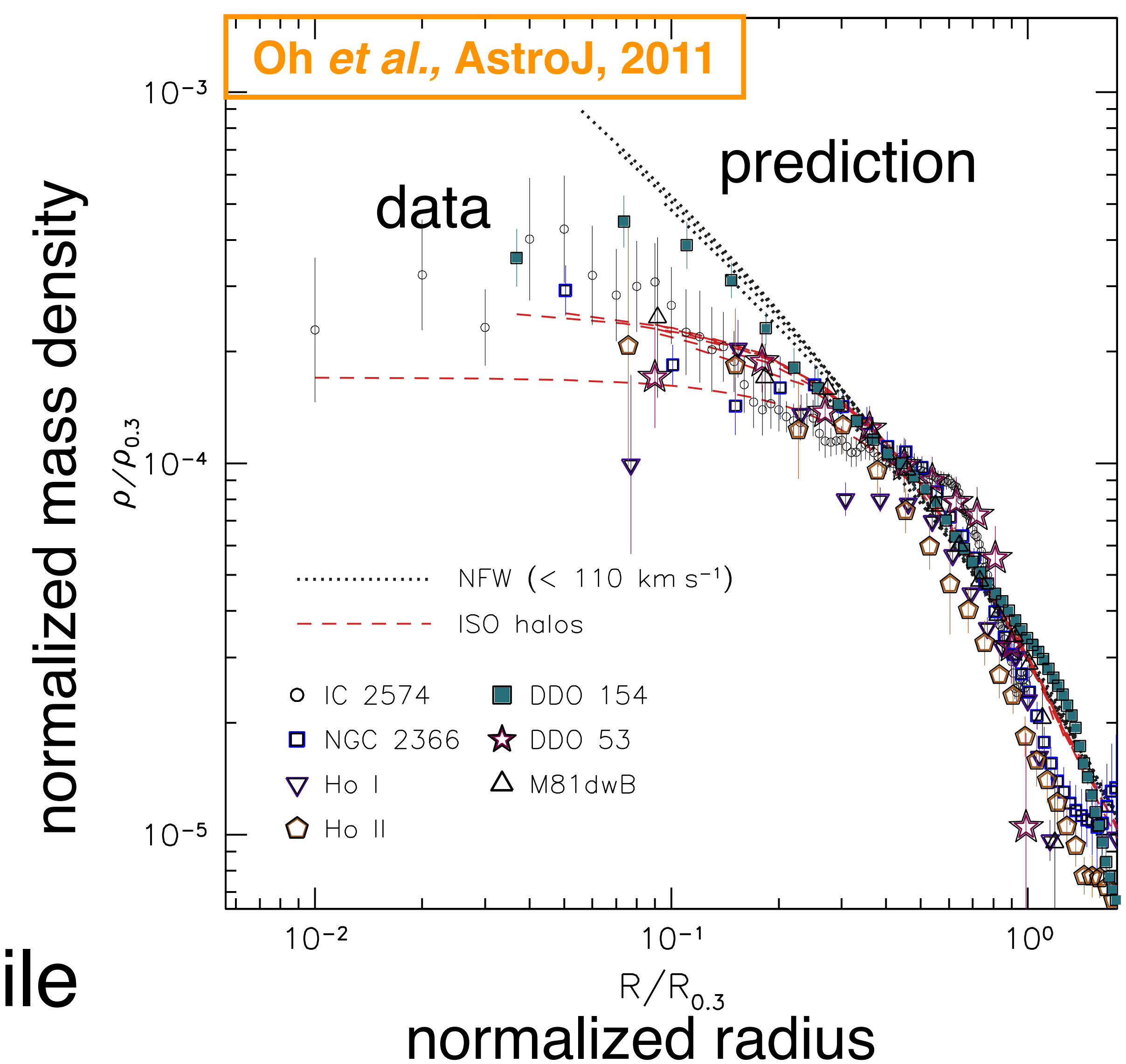
smaller for shorter Γ^{-1}

Halo structure



cusp vs core problem

- steeper inner profile than observed



For $r < r_c(V_k = V_{circ})$, density profile is shallower

$V_k = 100\,\mathrm{km/s}$, even with long $\Gamma^{-1} = 40\,\mathrm{Gyr}$, mildly lowers outer profile