ALPino/gravitino as decaying dark matter and cosmological signatures

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

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Based on
Kyu Jung Bae, AK, Hee Jung Kim, PRD, 2019 and in preparation
also work in progress w/ Toyokazu Sekiguchi, …

Nov. 6, 2019 @ IBS conference

Dark matter

Accumulated evidences from observations of the Universe

Known properties

- long-lived over the age of the Universe
- accounting for about $30\,\%$ of the present energy density of the Universe $\Omega_{\rm dm}h^2 \simeq 5\Omega_{\rm baryon}h^2 \simeq 0.12$
- feebly-interacting with photon and baryon
- not too hot to smear out primordial density contrast

Weakly-interacting massive particle (WIMP) paradigm

- satisfy above properties w/ new $\mathbb{Z}_2$symmetry
- originate from electroweak-scale new physics solving the hierarchy problem - WIMP miracle
- intensively investigated in direct/indirect detection experiments

No naturalness so far…

LHC discovery of $125\,\mathrm{GeV}$ Higgs and null-detection of top partners

- something wrong in the hierarchy problem and postulated solutions (including but not only electroweak-scale SUSY)

WIMP is no more as a miracle as we expected…

- new theoretical reasoning for WIMP? Arkani-Hamed and Dimopoulos, JHEP, 2005
    - mini-split SUSY Giudice and Romanino, NPB, 2004
        - sfermions $> 100\,\mathrm{TeV}$; gauginos $\sim \mathrm{TeV}$ Wells, PRD, 2005
            - $125\,\mathrm{GeV}$ Higgs
            - dark matter
            - precise grand unification

No convincing signals in direct/indirect detection experiments so far

- looking for hints in structure formation of the Universe?

Cold dark matter and beyond

Structure formation is a good laboratory of dark matter;
provided the properties; projected surveys

Cold dark matter (CDM) hypothesis - works well on large scales

- non-relativistic?
  - warm dark matter (WDM) $m \sim 1\,\mathrm{keV}$

    Bode, Ostriker, and Turok, ApJ, 2001 | Lovell *et al.*, MNRAS, 2012
- collisionless?
  - interacting (w/ radiation) dark matter (IDM) $\sigma/m \sim 10^{-9}\,\mathrm{cm}^2/\mathrm{g}$

    Boehm *et al.*, PRD, 2002 | ETHOS collaboration, MNRAS, 2016
  - self-interacting dark matter (SIDM) $\sigma/m \sim 1\,\mathrm{cm}^2/\mathrm{g}$

    Spergel and Steinhardt, PRL, 2000 | Tulin and Yu, Phys. Rept., 2018
- stable?
  - decaying dark matter (DDM) Peter, PRD, 2010 - relatively new - to be further studied

    $\boxed{0} \rightarrow 1 + \boxed{2}$ $\Gamma^{-1} \sim 10\,\mathrm{Gyr}$ V_{k} - kick velocity

What I will discuss

$\boxed{\text{ALPino}}_0 \rightarrow \text{ALP}_1 + \boxed{\text{gravitino}}_2$ - long-lived ✳ Hereafter $m_{\tilde{a}} > m_{3/2}$

- light & harmless

Underlying particle physics part 1

- lifetime vs kick velocity

Cosmological signatures part 2

- expansion history of the Universe
- dark matter halos

ALP flux part 3

- conversion to gamma-ray in the MW magnetic field

Underlying particle physics

SUSY ALP model

ALP - pseudo NG boson and harmless for large f_a

ALP SUSY multiplet

- sALP
- ALP
- ALPino

$$A = \frac{s + ia}{\sqrt{2}} + \sqrt{2}\theta\tilde{a} + \theta^2 F_A$$

→ ALPino mass ~ gravitino mass

Not necessarily, but $|1 - m_{3/2}/m_{\tilde{a}}| \ll 1 \leftrightarrow V_k \ll c$ is possible

Goto and Yamaguchi, PLB, 1992 | Chun, Kim, and Nilles, PLB, 1992 | Chun and Lucus, PLB, 1995

e.g. KSVZ-type model Kim, PRL, 1979 | Shifman, Vainshtein, and Zakharov, NPB, 1980

w/ minimal Kähler potential (✗ e.g., $K \supset |X|^2|S|^2/M_{\rm pl}^2$)

+ sequestered super potential $W \supset \lambda Z(XY - f^2) + W(S)$

→ tree-level $m_{\tilde{a}} = m_{3/2}$

+ 1-loop correction $W \supset kXQ\bar{Q}$ $\Delta m_{\tilde{a}}/m_{3/2} = k^2/(4\pi)^2$

Lifetime vs kick velocity

Assume that MSSM SUSY particles are heavier

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

Hamaguchi, Nakayama, and Tang, PLB, 2017

Lifetime

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

$$\simeq 11\,{\rm Gyr}\left(\frac{1\,{\rm TeV}}{m_{\tilde{a}}}\right)^3\left(\frac{100\,{\rm km/s}}{V_{\rm k}}\right)^5 \qquad 1-m_{3/2}/m_{\tilde{a}} \ll 1$$

Kick velocity

Bae, AK, and Kim, PRD, 2019

$$V_{\rm k}/c = \frac{1-m_{3/2}^2/m_{\tilde{a}}^2}{1+m_{3/2}^2/m_{\tilde{a}}^2}$$

$$\simeq 1-m_{3/2}/m_{\tilde{a}}$$

Parameter set $(\boxed{m_{\tilde{a}}, m_{3/2}}, m_a, f_a)$

$$\leftrightarrow (\Gamma_{\tilde{a}}^{-1}, V_{\rm k})$$

Cosmological signatures

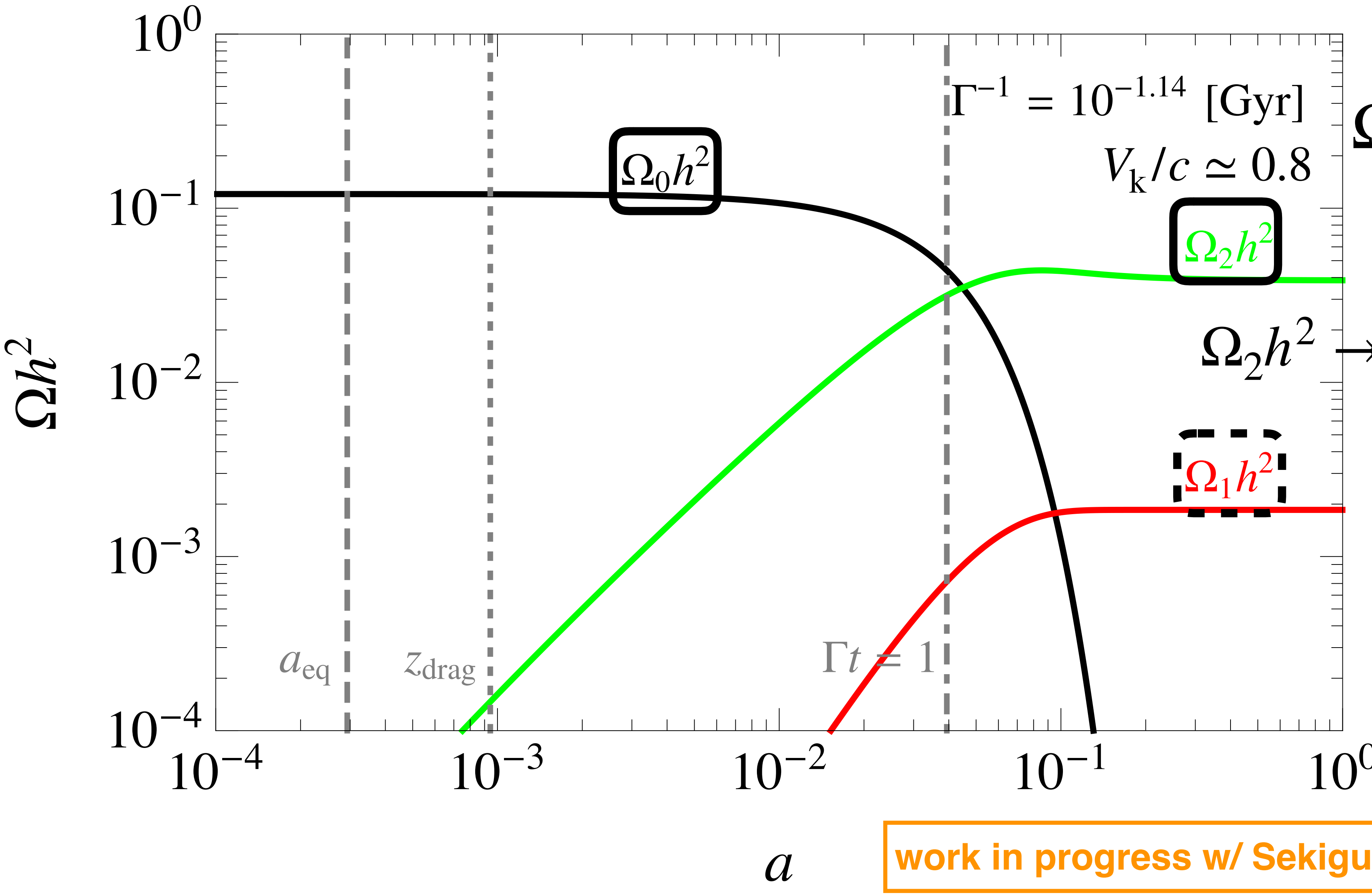
Expansion history of the Universe

$\boxed{\text{ALPino}}_0 \to \boxed{\text{ALP}}_1 + \boxed{\text{gravitino}}_2$

$$\Omega_{0(2)}h^2 = \frac{\rho_{0(2)}a^3}{\rho_{\rm crit}/h^2}$$

$$\Omega_1 h^2 = \frac{\rho_1 a^4}{\rho_{\rm crit}/h^2}$$

$$\Omega_2 h^2 \to \Omega_0 h^2 \sqrt{\frac{1 - V_{\rm k}/c}{1 + V_{\rm k}/c}}$$



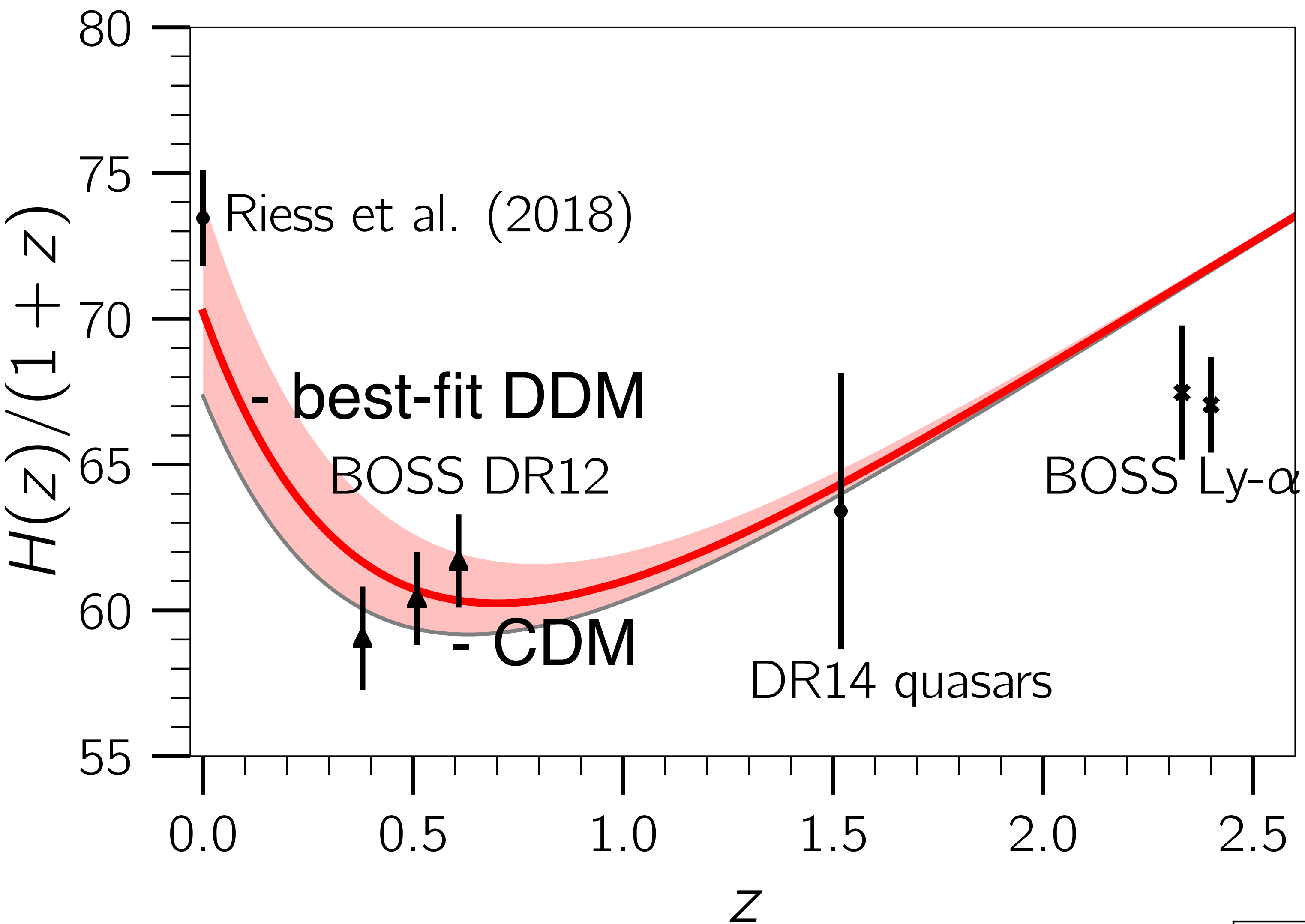
work in progress w/ Sekiguchi

lower H in the intermediate redshift

→ larger $\Omega_\Lambda h^2$ to compensate

→ larger H_0 at present

Hubble parameter

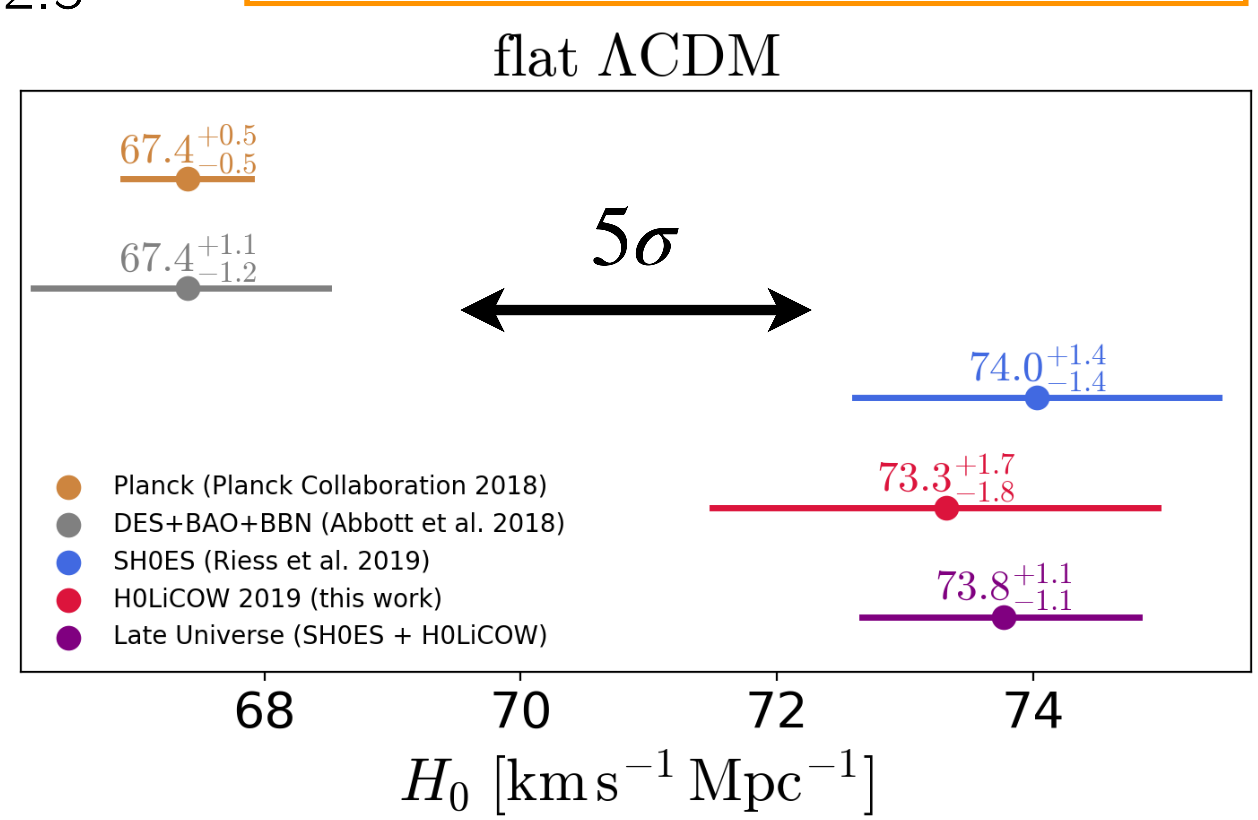


MCMC for low-redshift data

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, arXiv:1907.04869



Other parameters are fixed to be Planck values

- self-consistent analysis required

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

Jeans scale

With $V_{\rm k}/c \simeq 0.2$ and $\Gamma^{-1} \simeq 35\,{\rm Gyr}$, $30\,\%$ of DDM decays by today

Jeans scale

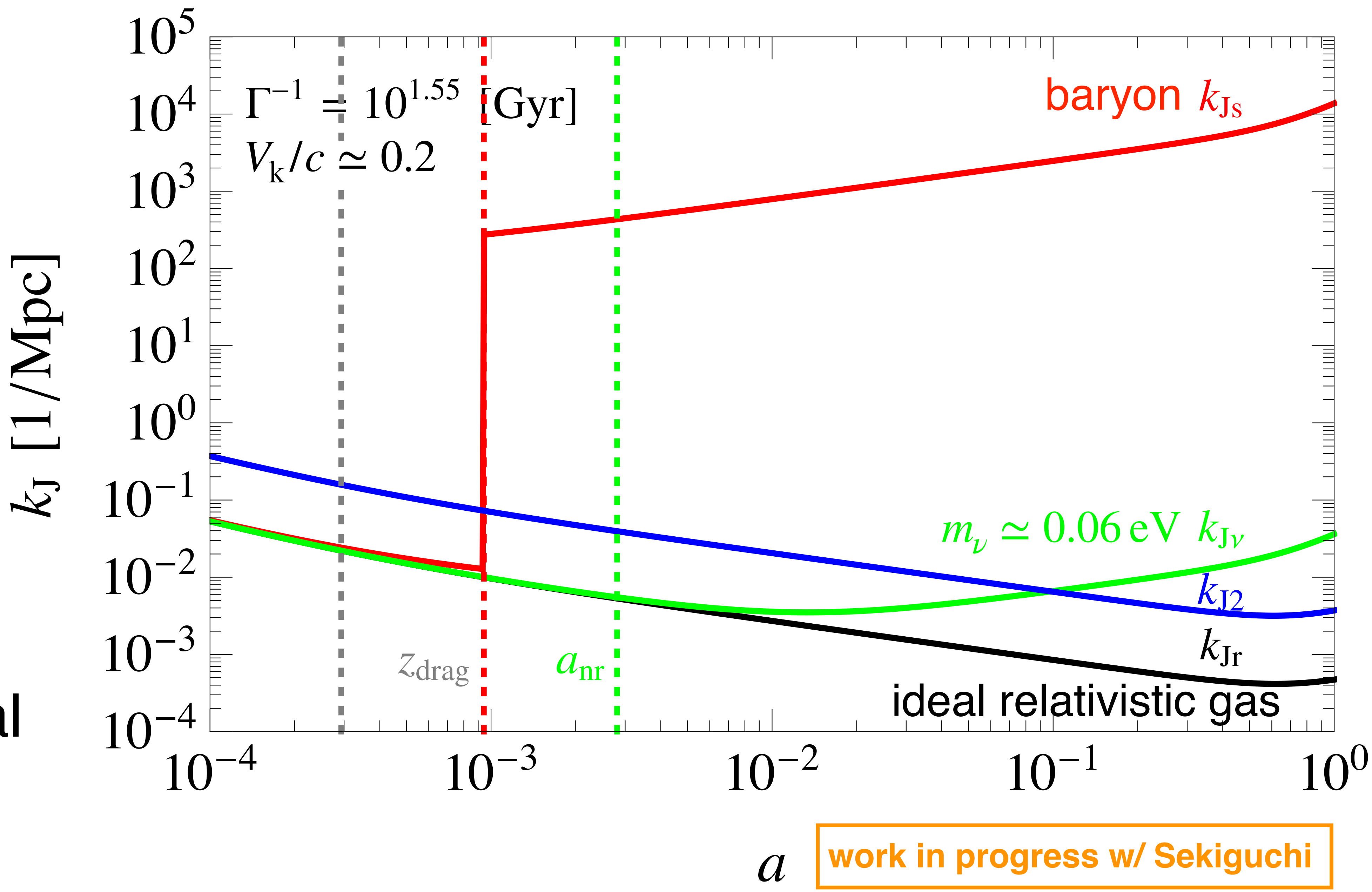
$k > k_{\rm J}$

- pressure > gravity

$k < k_{\rm J}$

- gravity > pressure

→ gravitational collapse

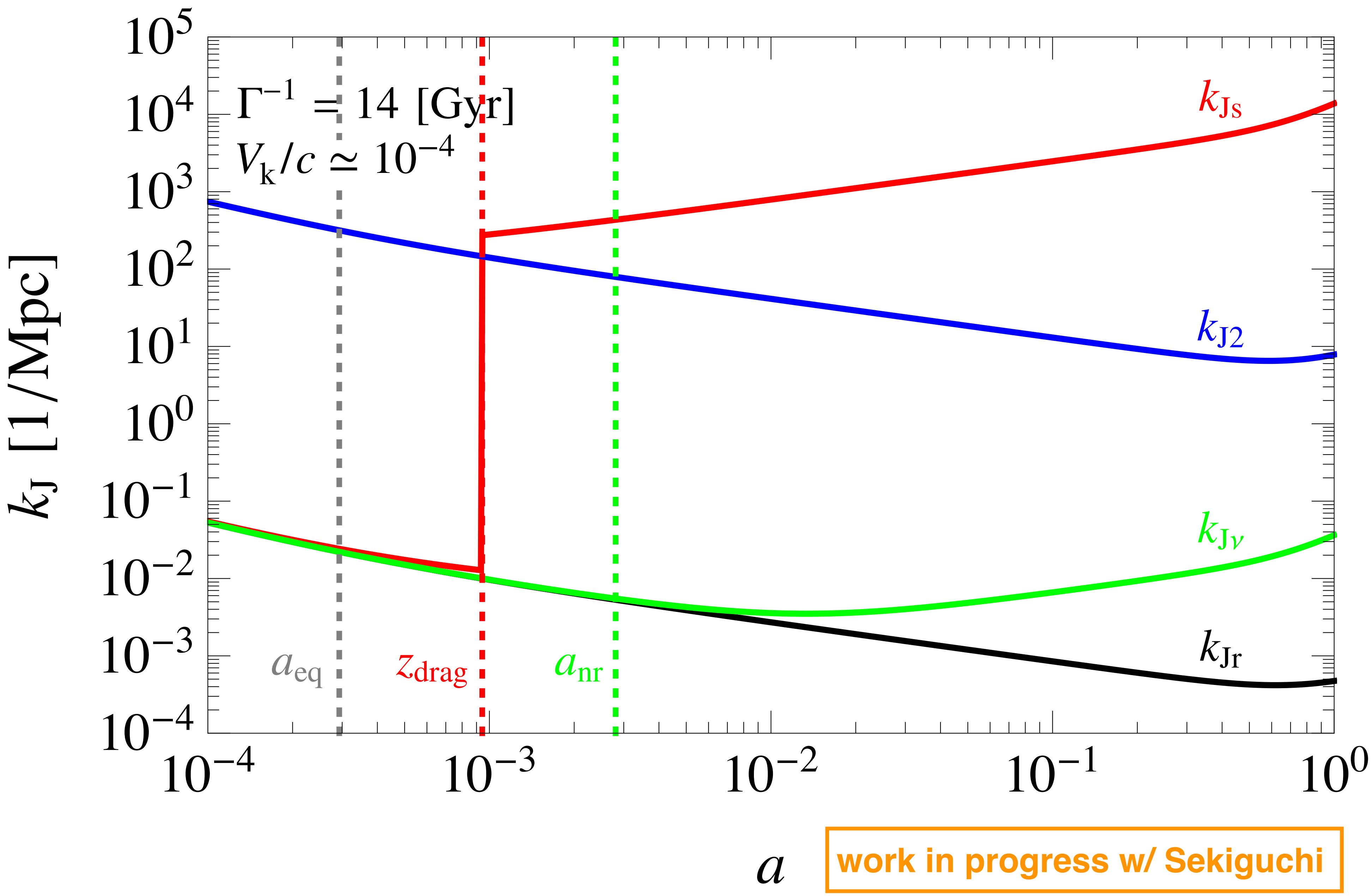


Jeans scale of daughter DM is $k_{\rm J2} \sim 1/{\rm Gpc}$ at present

→ hot component

Jeans scale

With $V_{\rm k} \simeq 30\,{\rm km/s}$ and $\Gamma^{-1} \simeq 14\,{\rm Gyr}$, $60\,\%$ of DDM decays by today

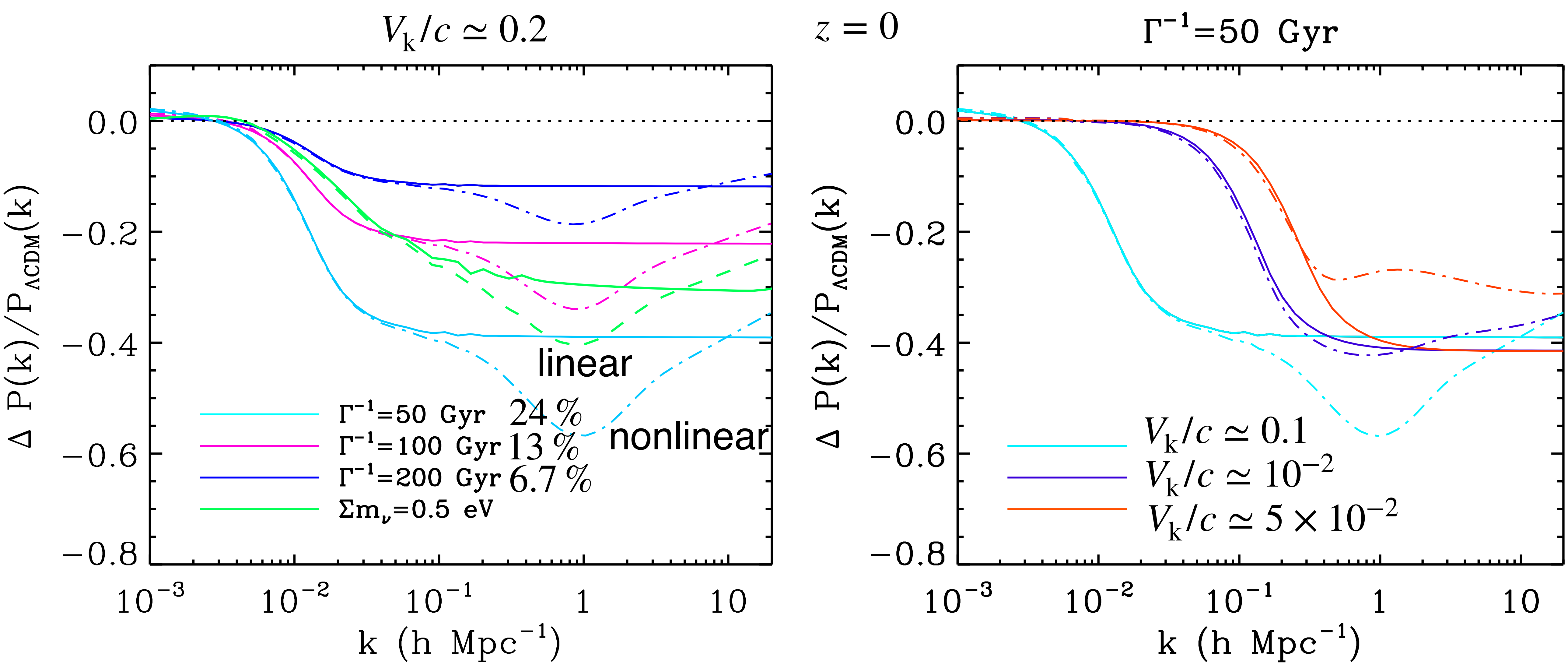


work in progress w/ Sekiguchi

Jeans scale of daughter DM is $k_{\rm J2} \sim 10/{\rm Mpc}$ at present

→ warm component

Matter power spectrum



Wang and Zentner, PRD, 2012

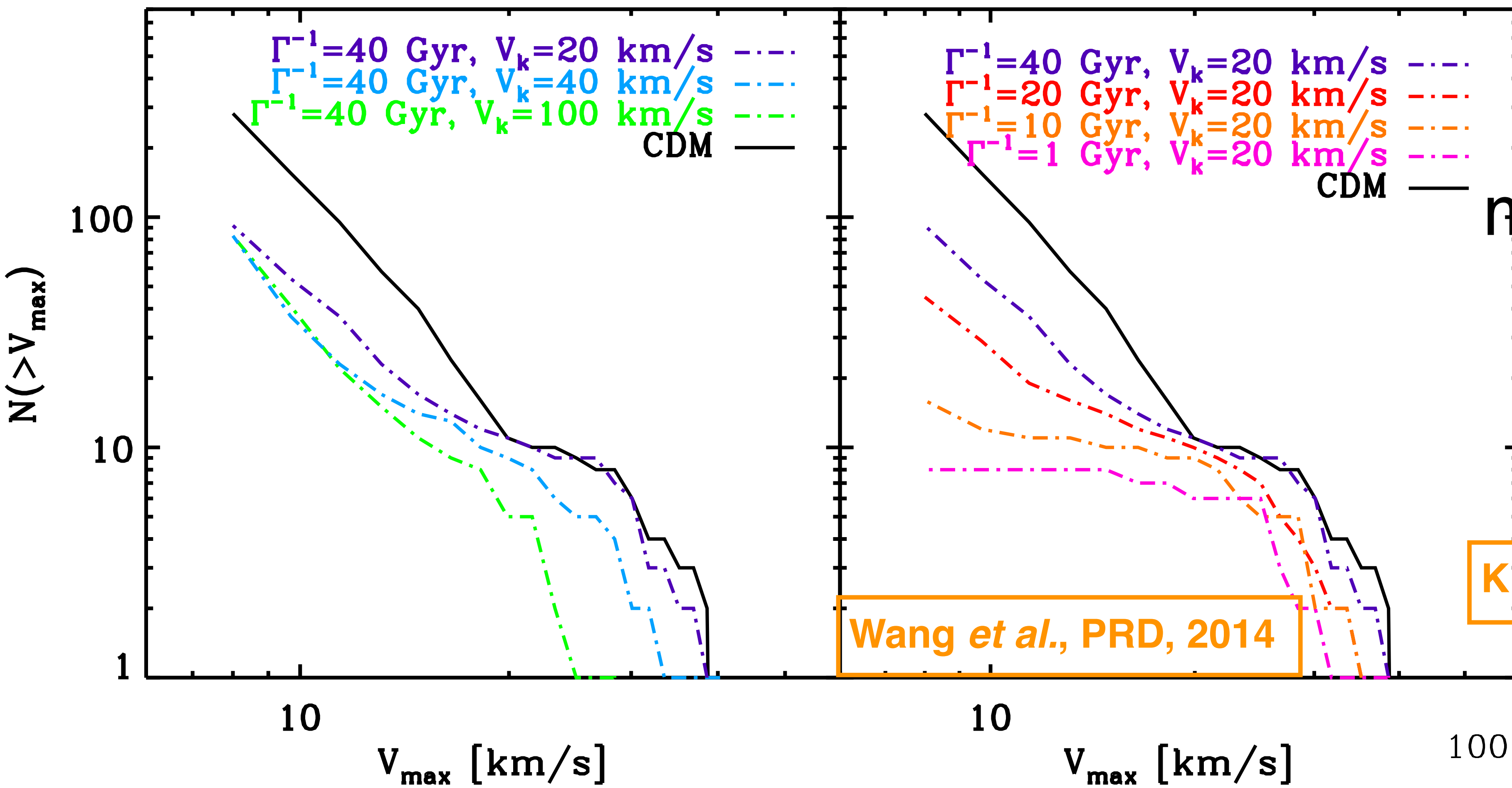
Suppression of the matter power spectrum

→ constraints from weak lensing $z = 0\text{-}1$ $k = 0.1\text{-}1/\mathrm{Mpc}$

Lyman-α forest $z = 2\text{-}4$ $k = 0.1\text{-}10/\mathrm{Mpc}$

$t \simeq 2\,\mathrm{Gyr}$ at $z = 3$ → hard to constrain $\Gamma^{-1} > 100\,\mathrm{Gyr}$

MW satellites

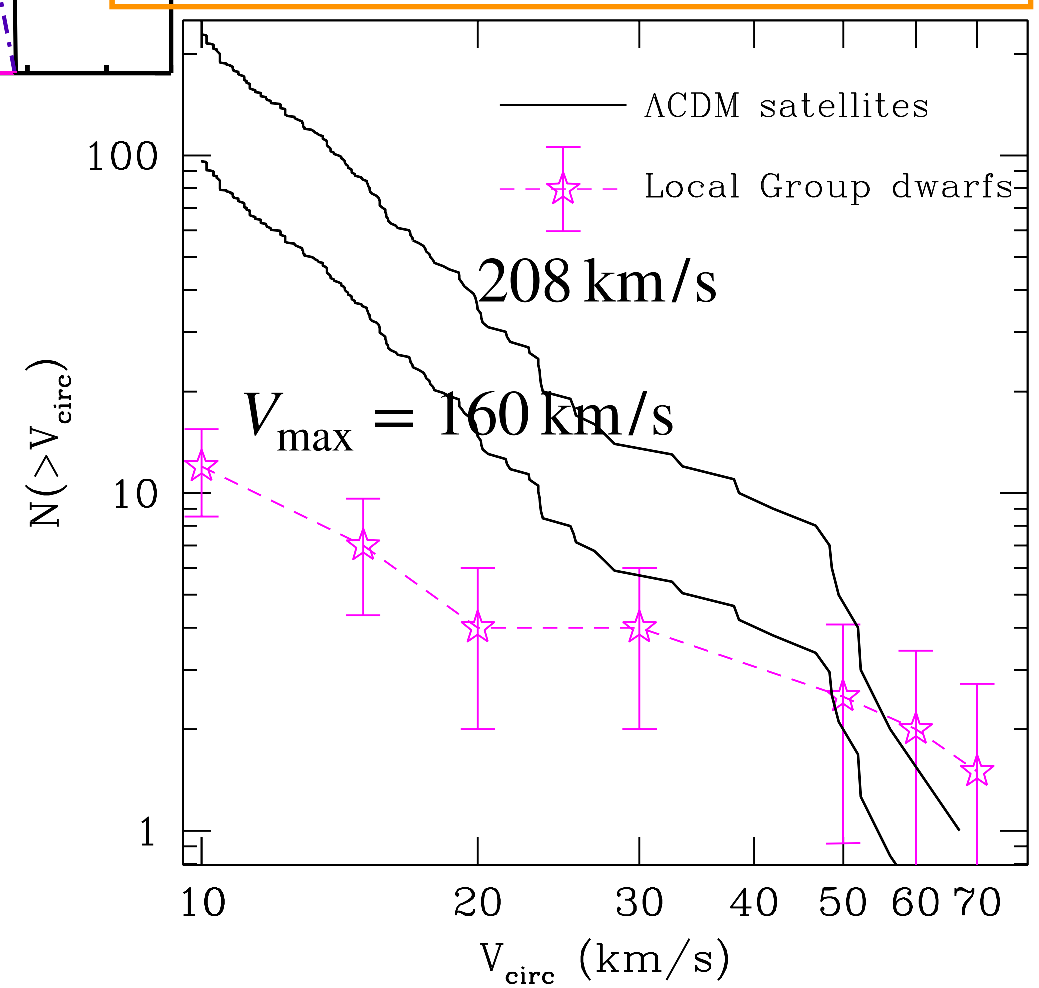


Wang *et al.*, PRD, 2014

missing satellite problem

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

Kratsov, Advances in Astronomy, 2010

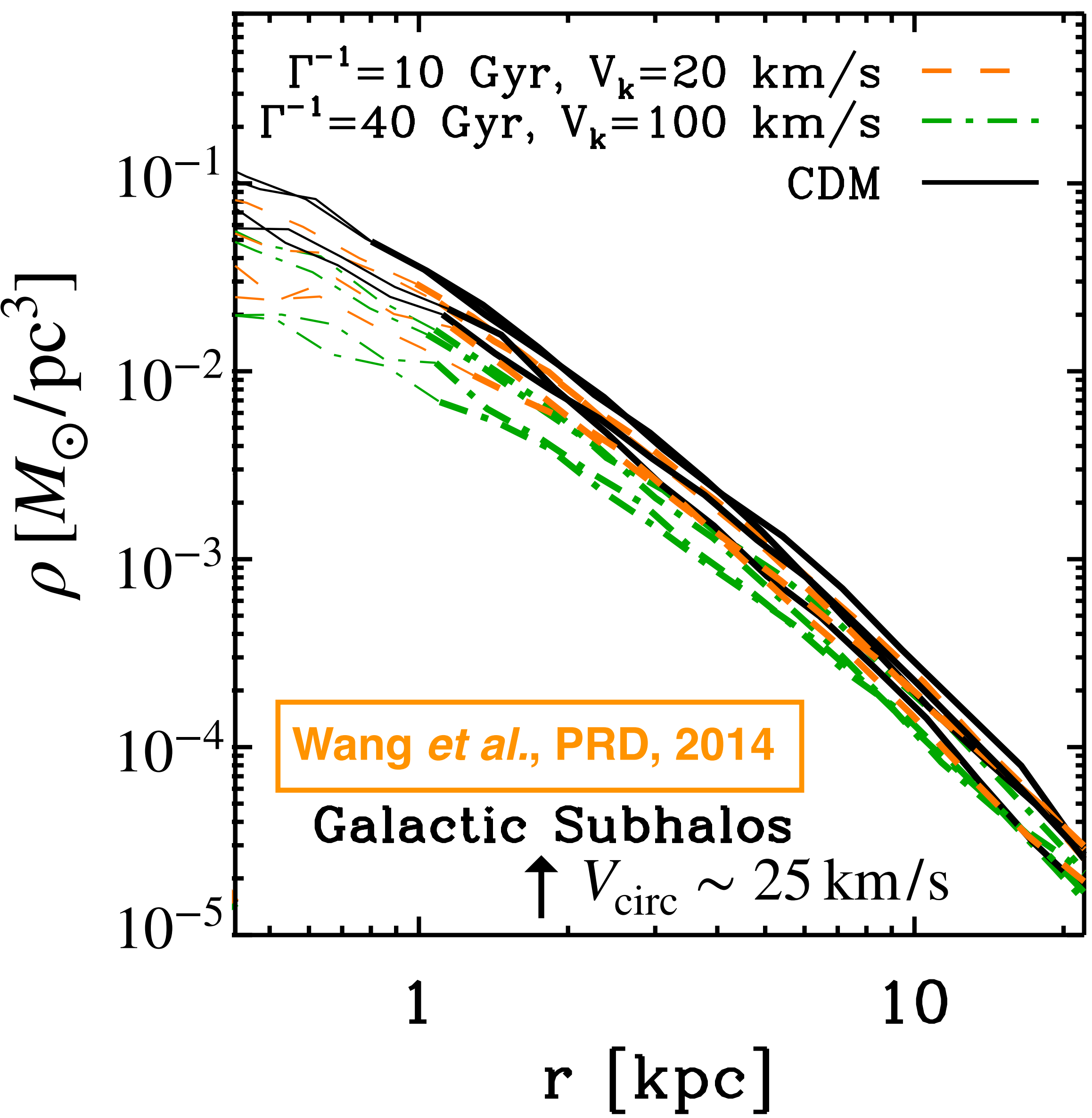


$\boxed{V_{\rm k} \text{ vs } V_{\rm max}}$

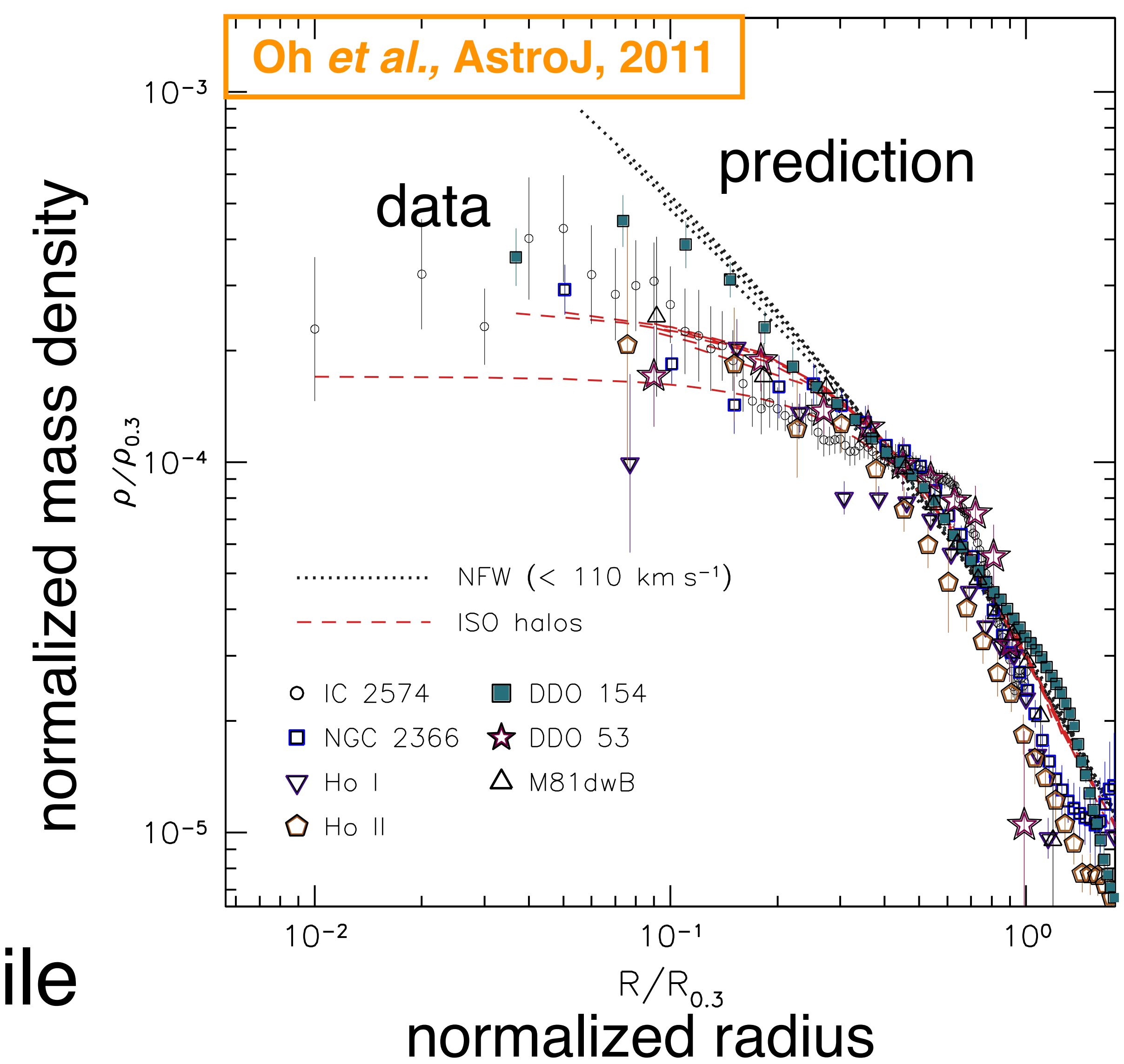
For $V_{\rm k} > V_{\rm max}$, number of subhalos is almost insensitive to $V_{\rm k}$

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

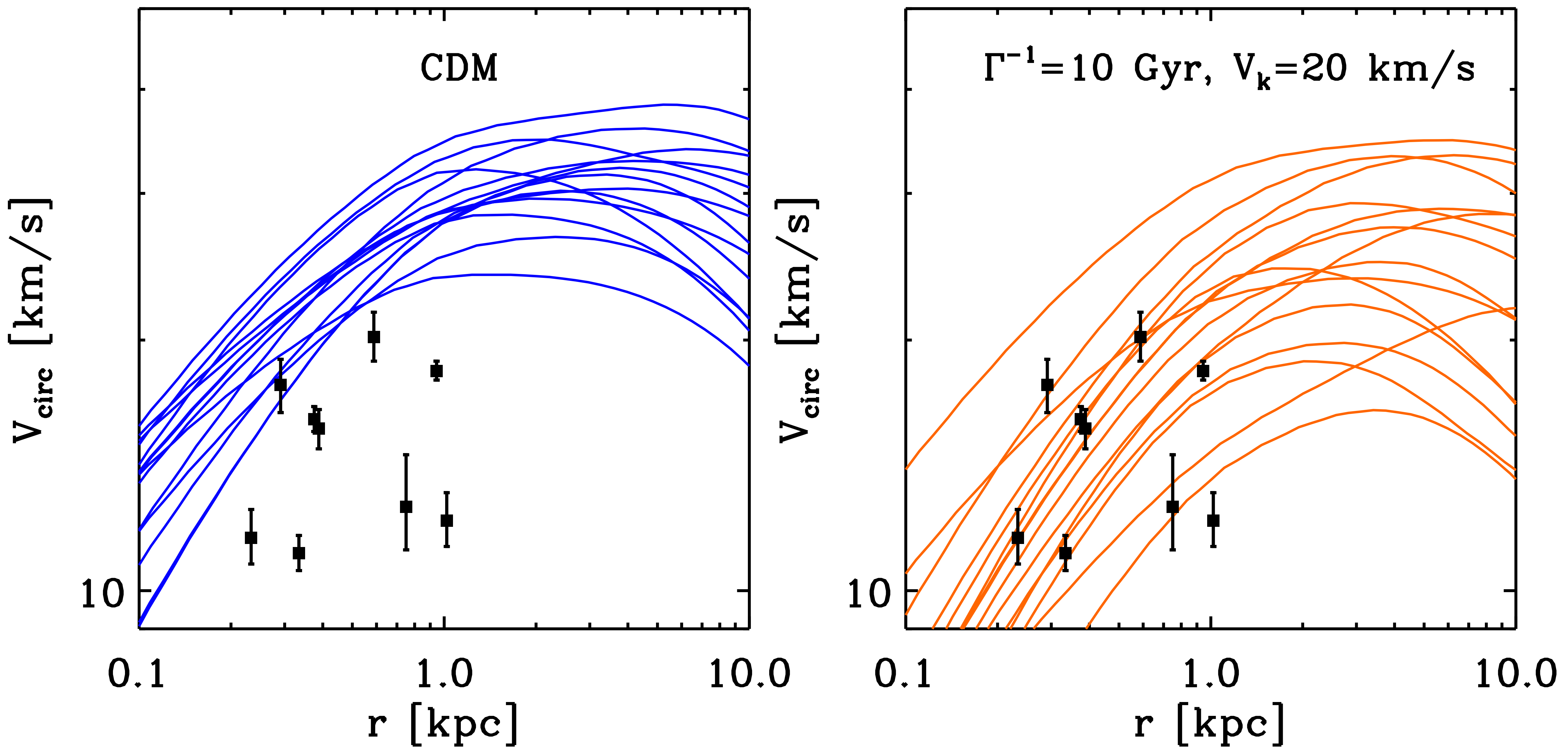
$V_k = 100\,\mathrm{km/s}$, even with long $\Gamma^{-1} = 40\,\mathrm{Gyr}$, mildly lowers outer profile

Halo structure

too-big-to-fail problem

- ~ 10 biggest subhalos are missing

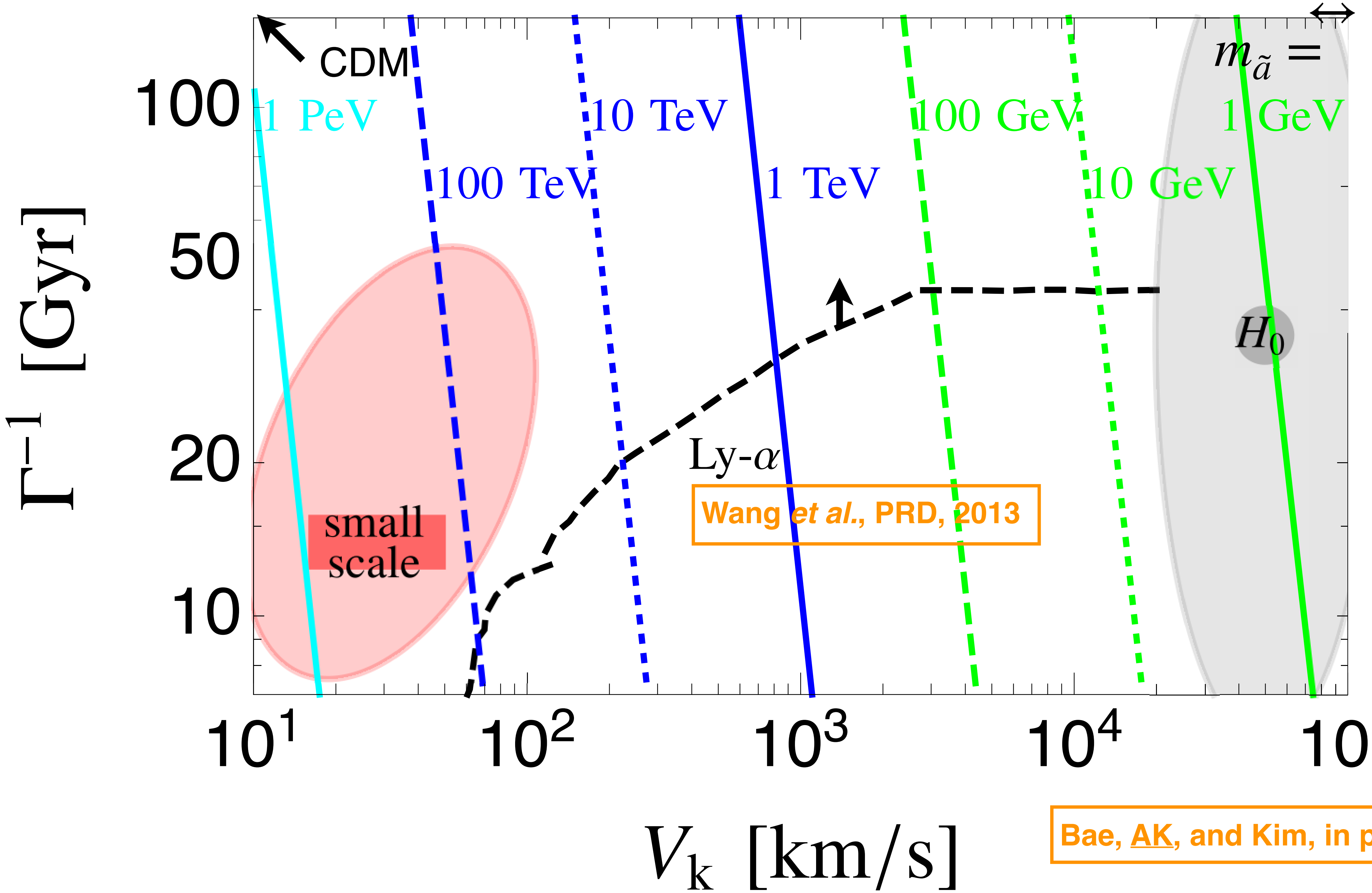
Wang *et al.*, PRD, 2014



ALPino parameter space

Parameter set $(\boxed{m_{\tilde{a}}, m_{3/2}}, m_a, f_a)$

$\leftrightarrow (\Gamma_{\tilde{a}}^{-1}, V_{\mathrm{k}})$

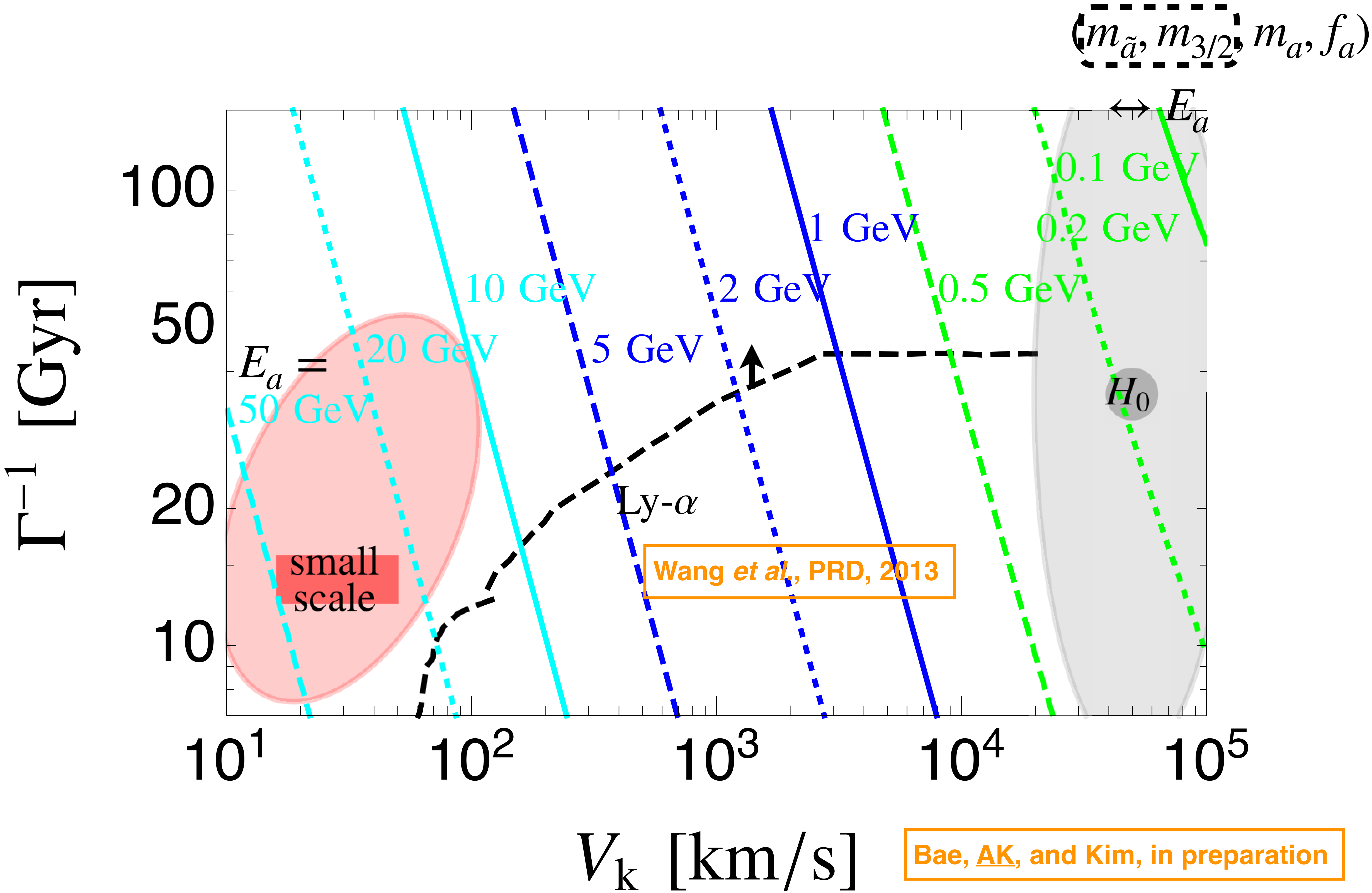


Bae, AK, and Kim, in preparation

$\ast$ shaded regions are to be clarified further

ALP flux

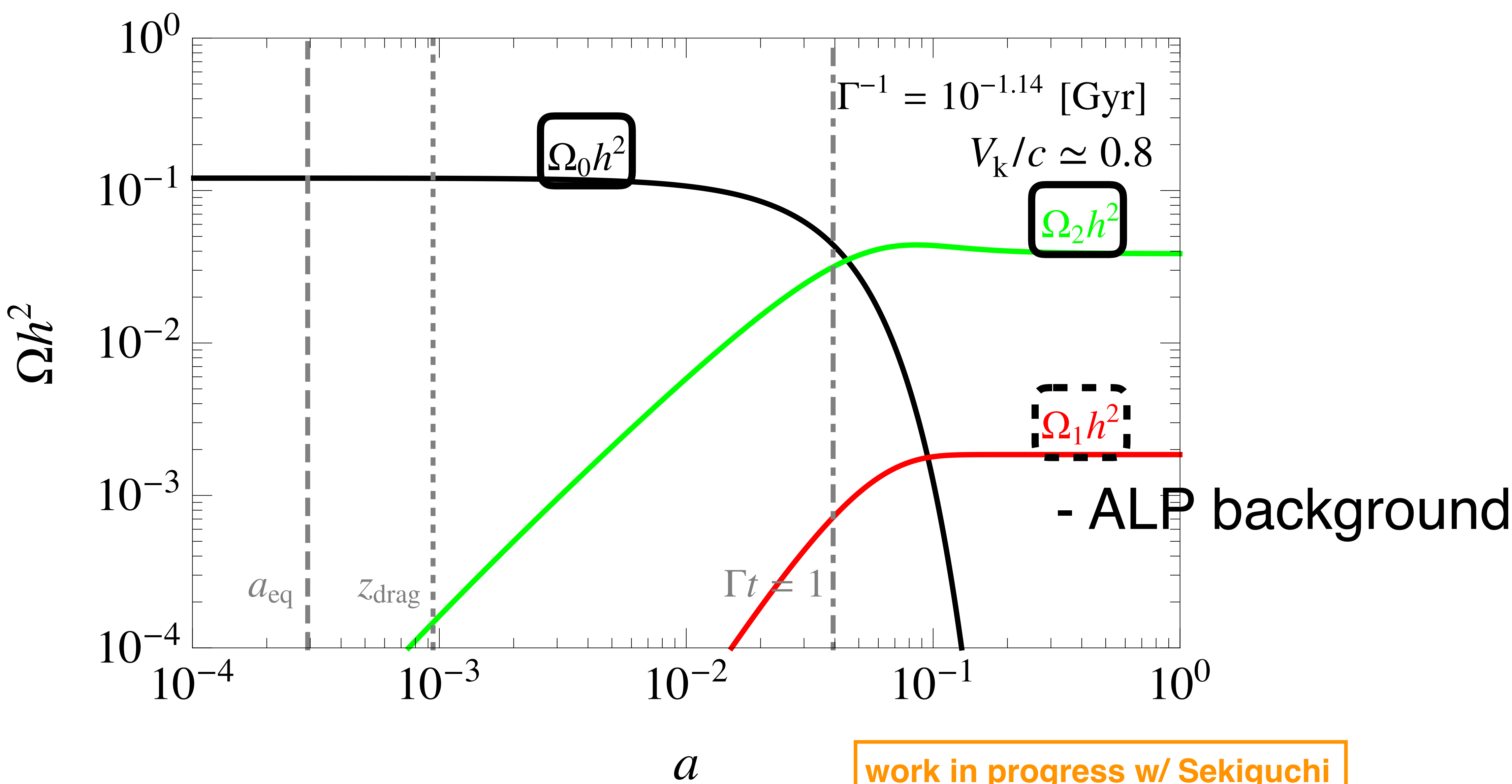
ALP energy at emission



Emitted ALP has $E_a = 0.1\text{-}100\,\mathrm{GeV}$ up to red-shifting

Cosmic ALP background

$\boxed{\text{ALPino}}_0 \rightarrow \boxed{\text{ALP}}_1 + \boxed{\text{gravitino}}_2$



work in progress w/ Sekiguchi

For $\Gamma^{-1} < t_{age} \simeq 13.8\,\mathrm{Gyr}$, emitted ALPs predominantly contributes to diffuse background

Galactic ALP emission

For $\Gamma^{-1} < t_{\rm age} \simeq 13.8\,{\rm Gyr}$, emitted ALPs predominantly contributes to Galactic monochromatic flux

$$E_a^2 \frac{d^2\Phi_a}{dE_a d\Omega} \simeq 6\times 10^3\, J_{\rm D,ROI}\, e^{-\Gamma t_{\rm age}}\, {\rm MeV/cm^2/s/sr}$$

$$\times \left(\frac{E_a}{47\,{\rm GeV}}\right)^2 \left(\frac{750\,{\rm TeV}}{m_{\tilde a}}\right) \left(\frac{10\,{\rm Gyr}}{\Gamma_{\tilde a}^{-1}}\right)^{-1}$$

$$\times \left(\frac{1\,{\rm GeV}}{\Delta E}\right) \left(\frac{1\,{\rm sr}}{\Delta\Omega_{\rm ROI}}\right)$$

Bae, AK, and Kim, PRD, 2019

$\sim 10^6$ larger than diffuse gamma-ray flux in Fermi-LAT

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

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

Fermi-LAT collaboration, ApJ, 2012

ALP-photon conversion

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

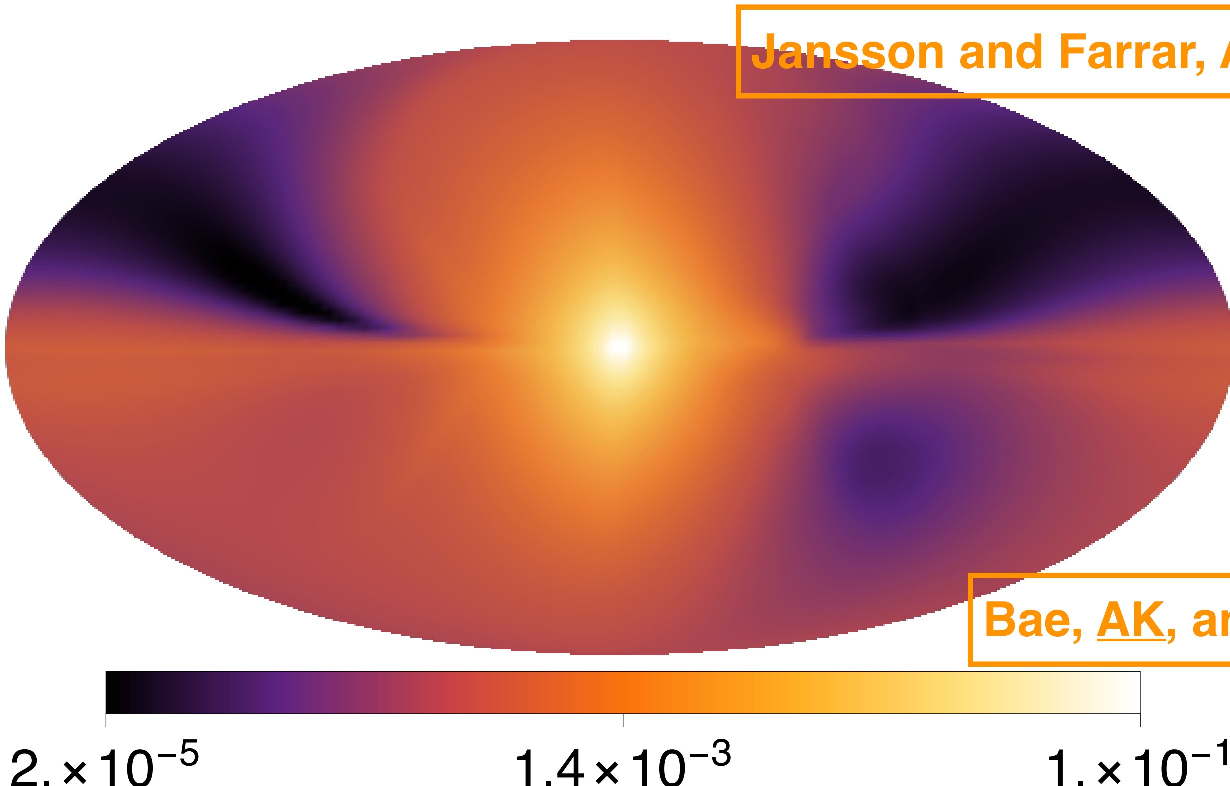
Adiabatic conversion rate through Galactic magnetic field

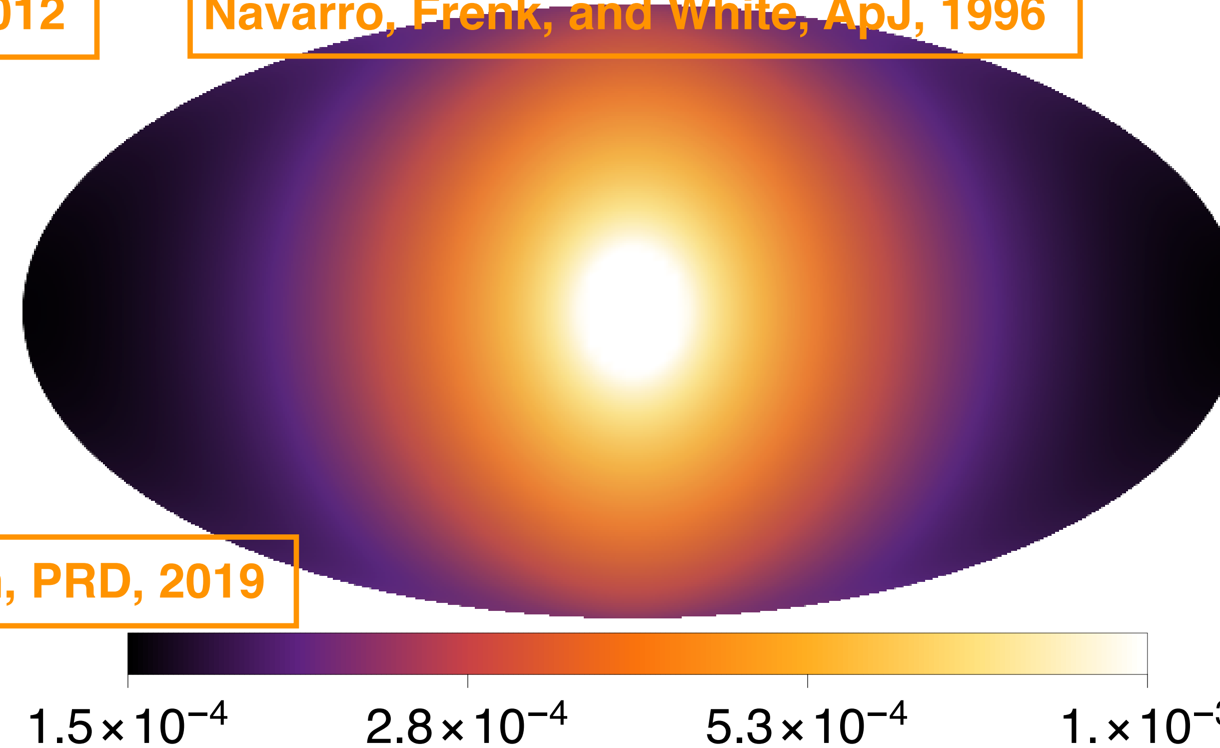
$$P_{a\gamma}(s,\Omega) \simeq 2\times 10^{-7} \left|\frac{B_T(s,\Omega)}{\mu\mathrm{G}}\right|^2 \left(\frac{10^{-8}\,\mathrm{eV}}{m_a}\right)^4 \left(\frac{g_{a\gamma}}{10^{-13}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{E_\gamma}{47\,\mathrm{GeV}}\right)^2$$

Morphology - convolution of $B_T(s,\Omega)$ and $\rho_{\rm dm}(s,\Omega)$ $\quad m_a^2/E_a \gg g_{a\gamma}|B_T|$

Jansson and Farrar, ApJ, 2012

Navarro, Frenk, and White, ApJ, 1996

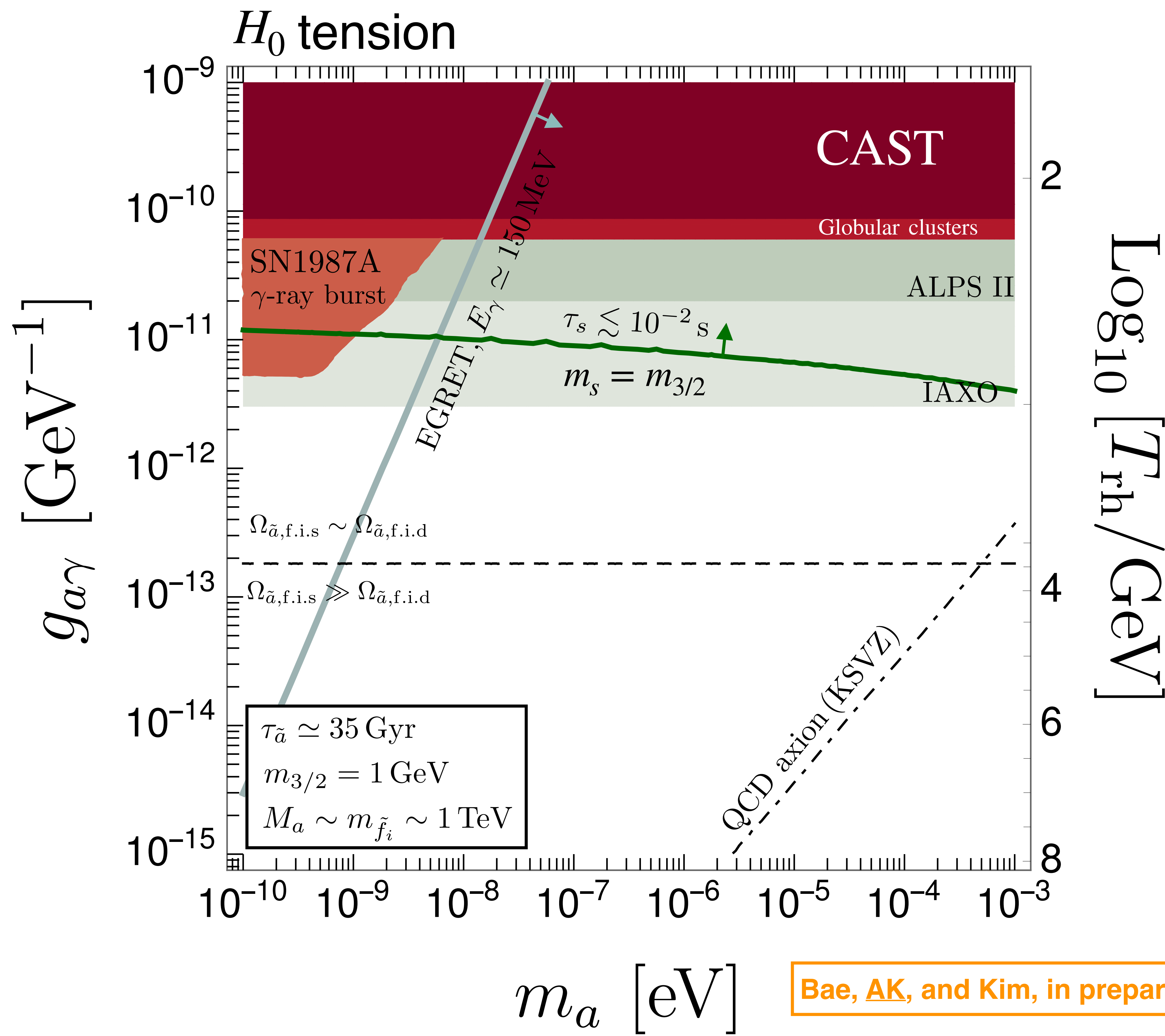




Bae, AK, and Kim, PRD, 2019

decay + conversion $\quad E_\gamma^2 \dfrac{d^2\Phi_\gamma}{dE_\gamma d\Omega}$ [MeV/cm^2/s/sr] $\quad$ direct decay

ALP parameter space



$(\boxed{m_{\tilde{a}}, m_{3/2}}, \boxed{m_a, f_a}) \leftrightarrow E_a$

Production from thermal bath around reheating

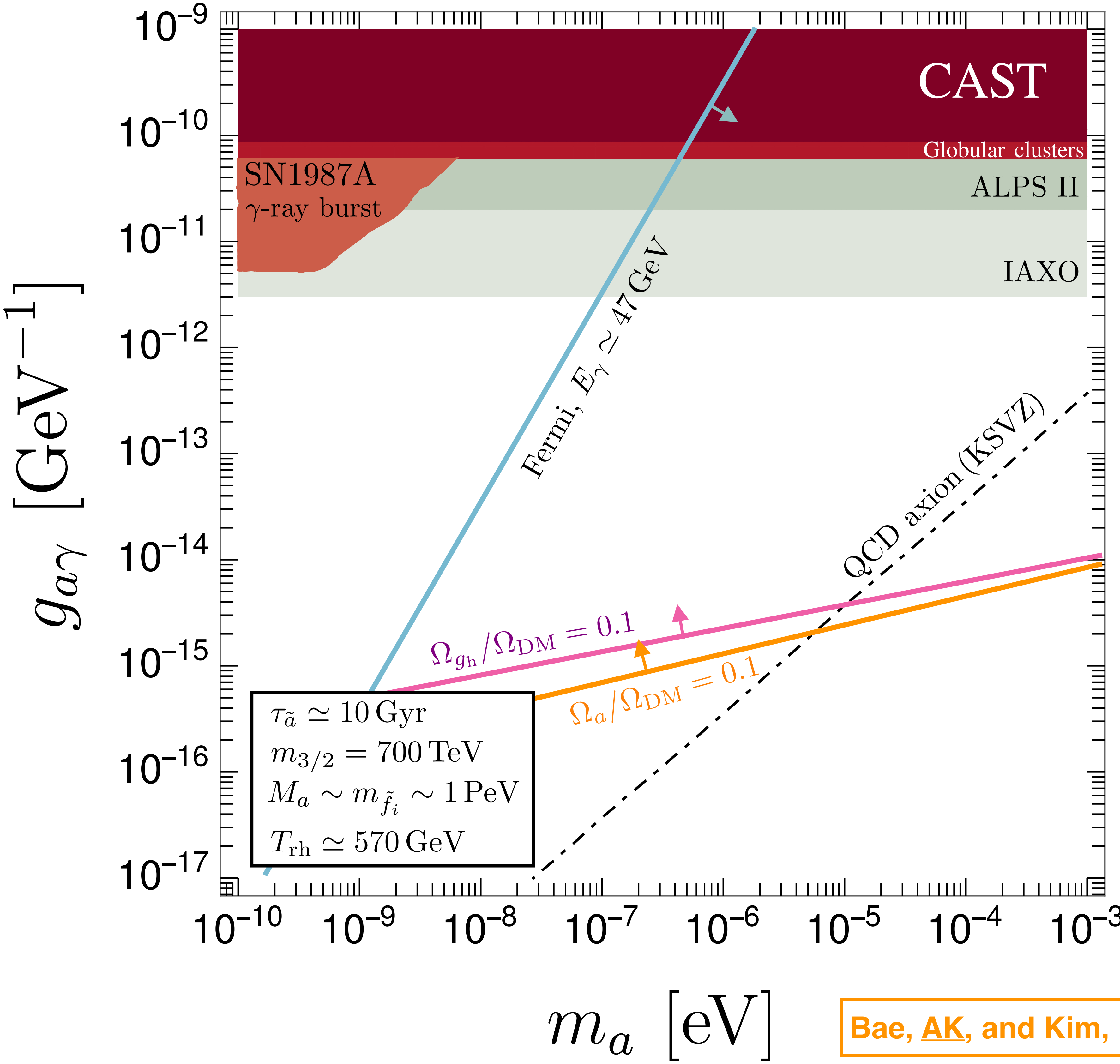
Bae, AK, and Kim, in preparation

ALP parameter space

Small-scale issues

$(\boxed{m_{\tilde{a}}, m_{3/2}}, \boxed{m_a, f_a})$

$\leftrightarrow E_a$



Production from decay of freeze-out LOSP

Bae, AK, and Kim, in preparation

Summary

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

- relatively new bottom-up approach

    - to be further understood

- ALPino/gravitino as underlying physics $(m_{\tilde{a}}, m_{3/2}, m_a, f_a)$

Cosmological signature $(\boxed{m_{\tilde{a}}, m_{3/2}}, m_a, f_a)$

- change in expansion history of the Universe $\leftrightarrow (\Gamma_{\tilde{a}}^{-1}, V_\mathrm{k})$

  $V_\mathrm{k}/c \sim 0.1$

  → possible solution to H_0 tension

- change in galactic-scale structure formation $V_\mathrm{k} \sim 10\,\mathrm{km/s}$

  → mitigating small-scale issues

ALP flux - direct detection? $(m_{\tilde{a}}, m_{3/2}, \boxed{m_a, f_a})$

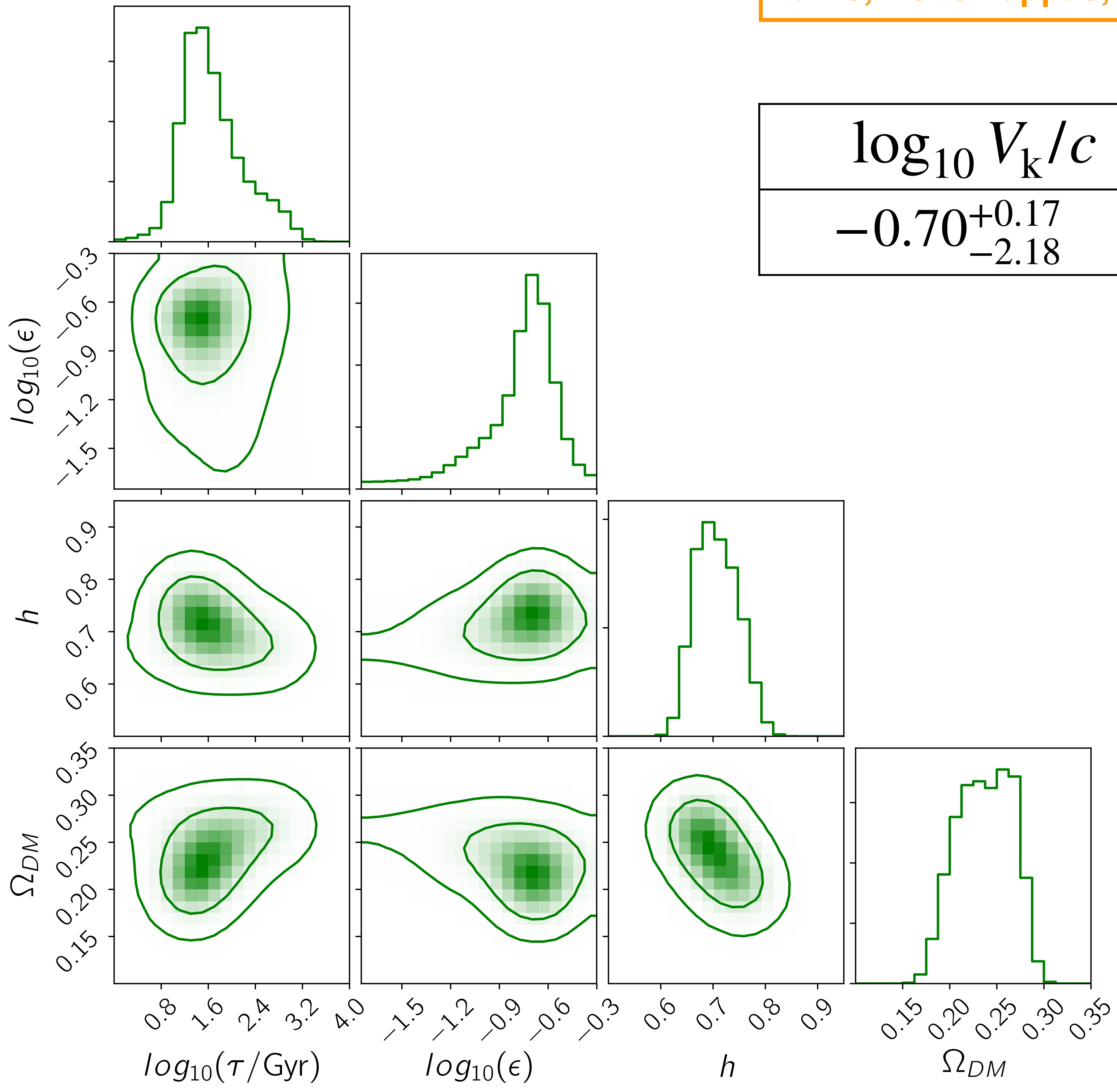
- ALP-photon conversion in Galactic magnetic field $\leftrightarrow E_a$

  → monochromatic gamma-ray flux with unique morphology

Thank you for your attention

Hubble parameter

MCMC for low-redshift data

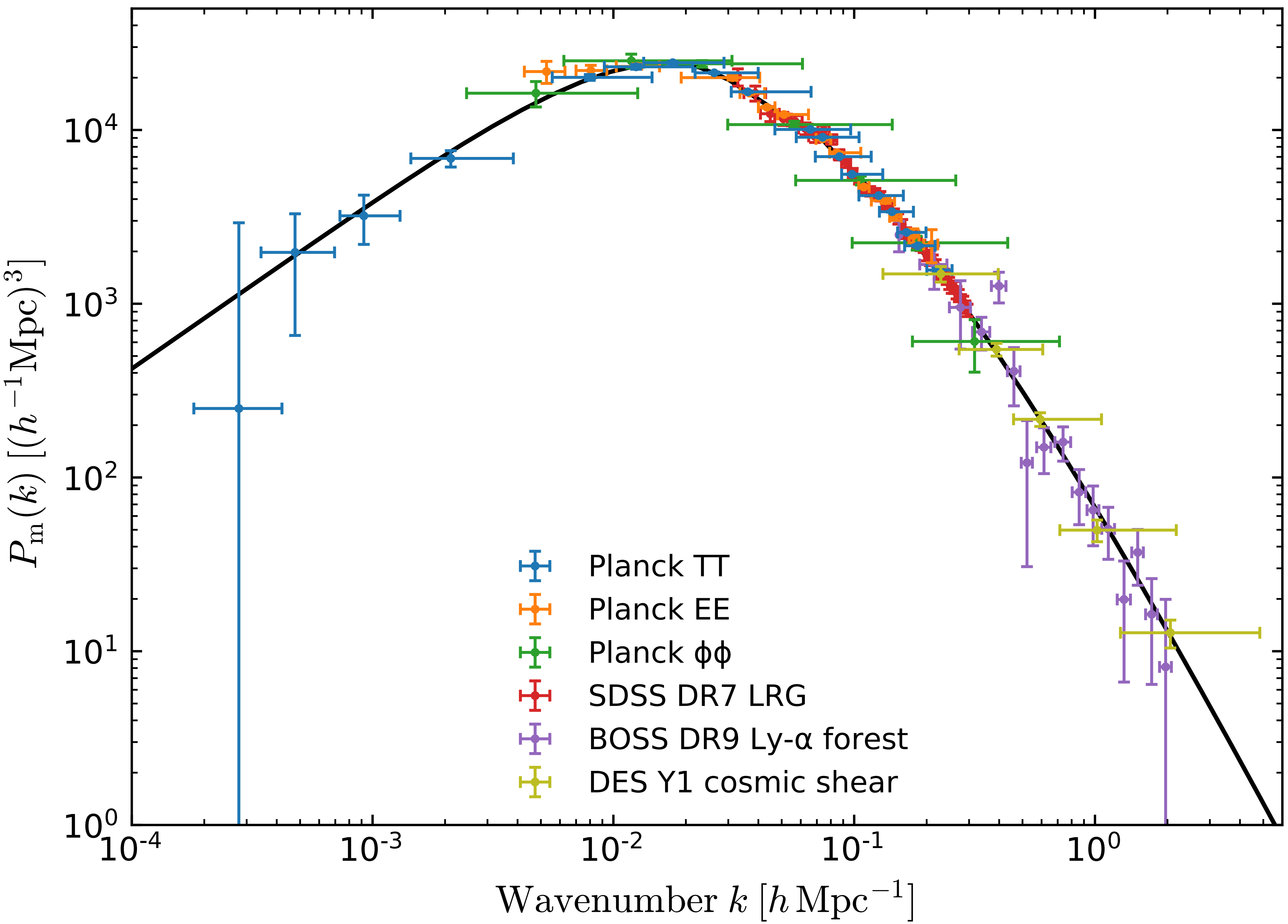


Vattis, Koushiappas, and Loeb, PRD, 2019

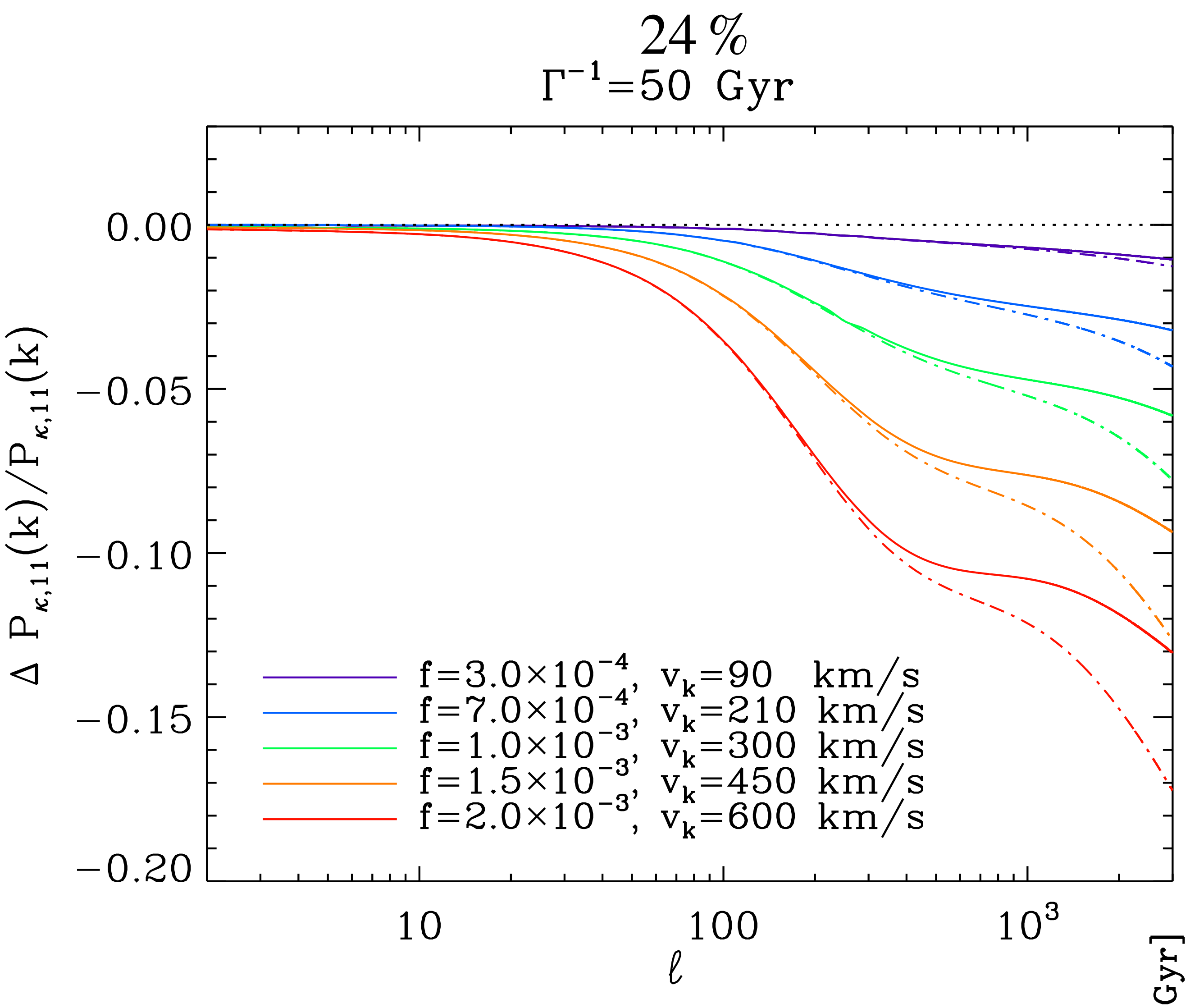
$\log_{10} V_{\mathrm{k}}/c$	$\log_{10}(\Gamma^{-1}/\mathrm{Gyr})$
$-0.70^{+0.17}_{-2.18}$	$1.55^{+0.63}_{-0.25}$

Probing matter power spectrum

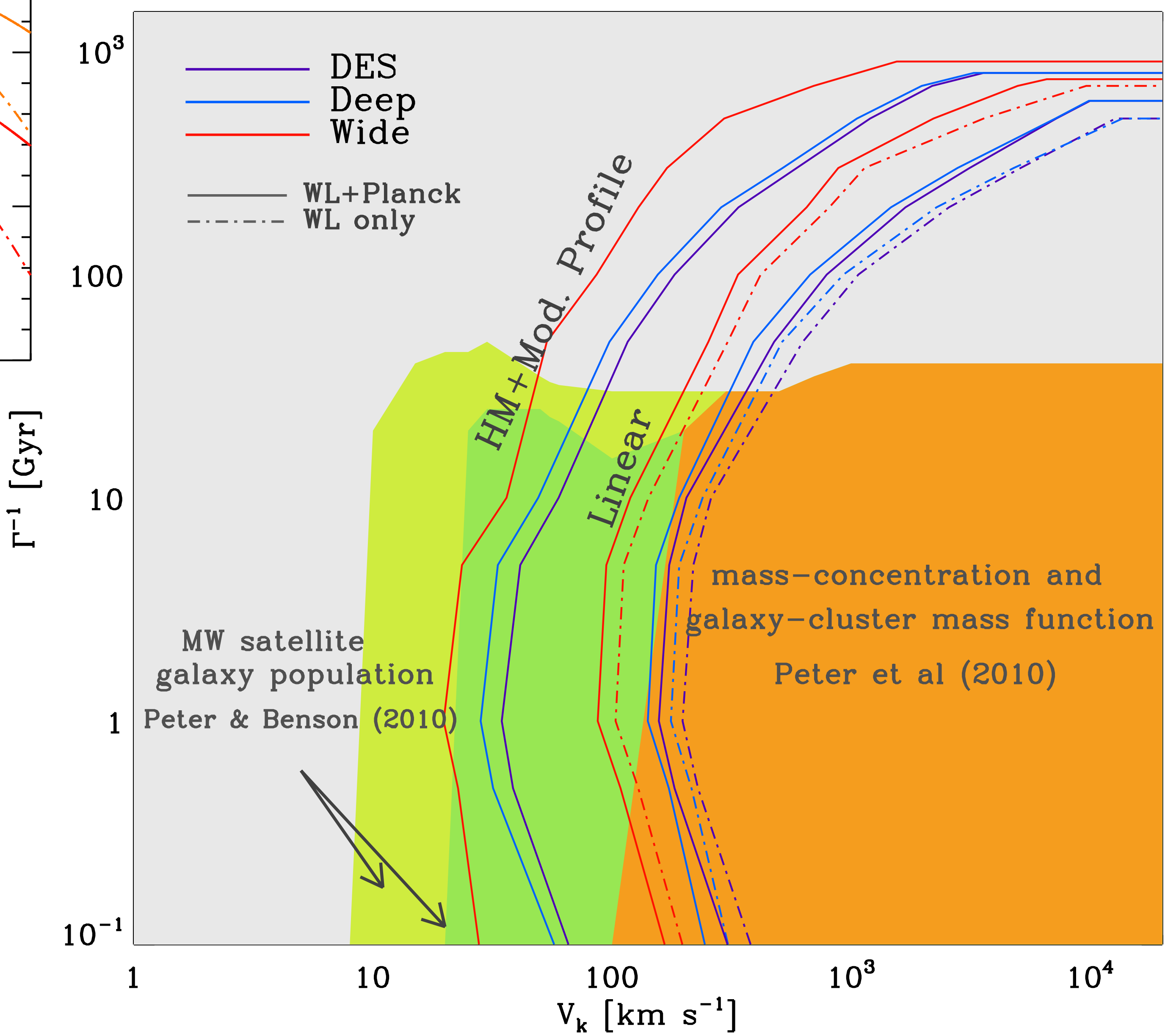
Planck collaboration, arXiv:1807.06205



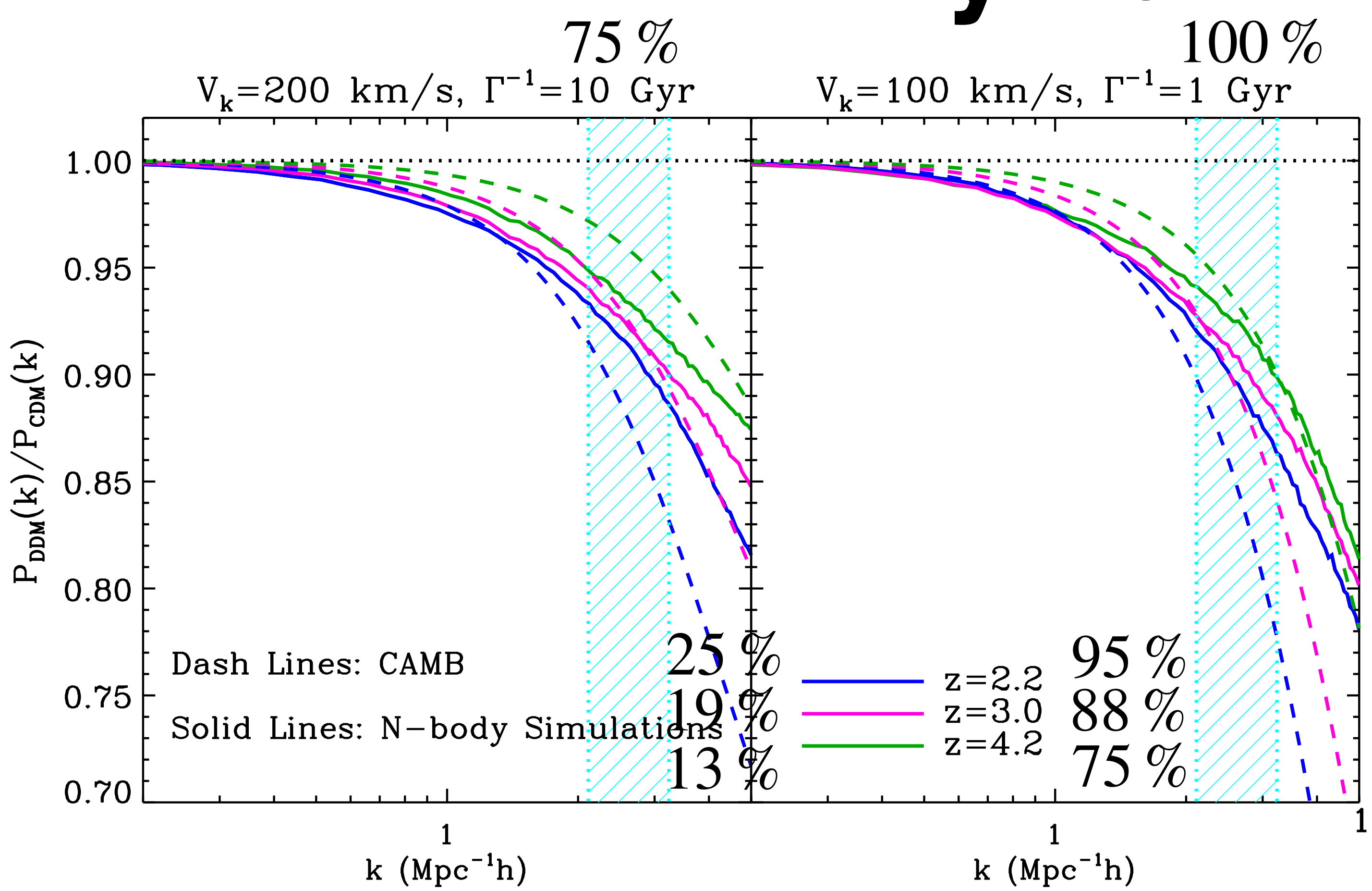
Weak lensing



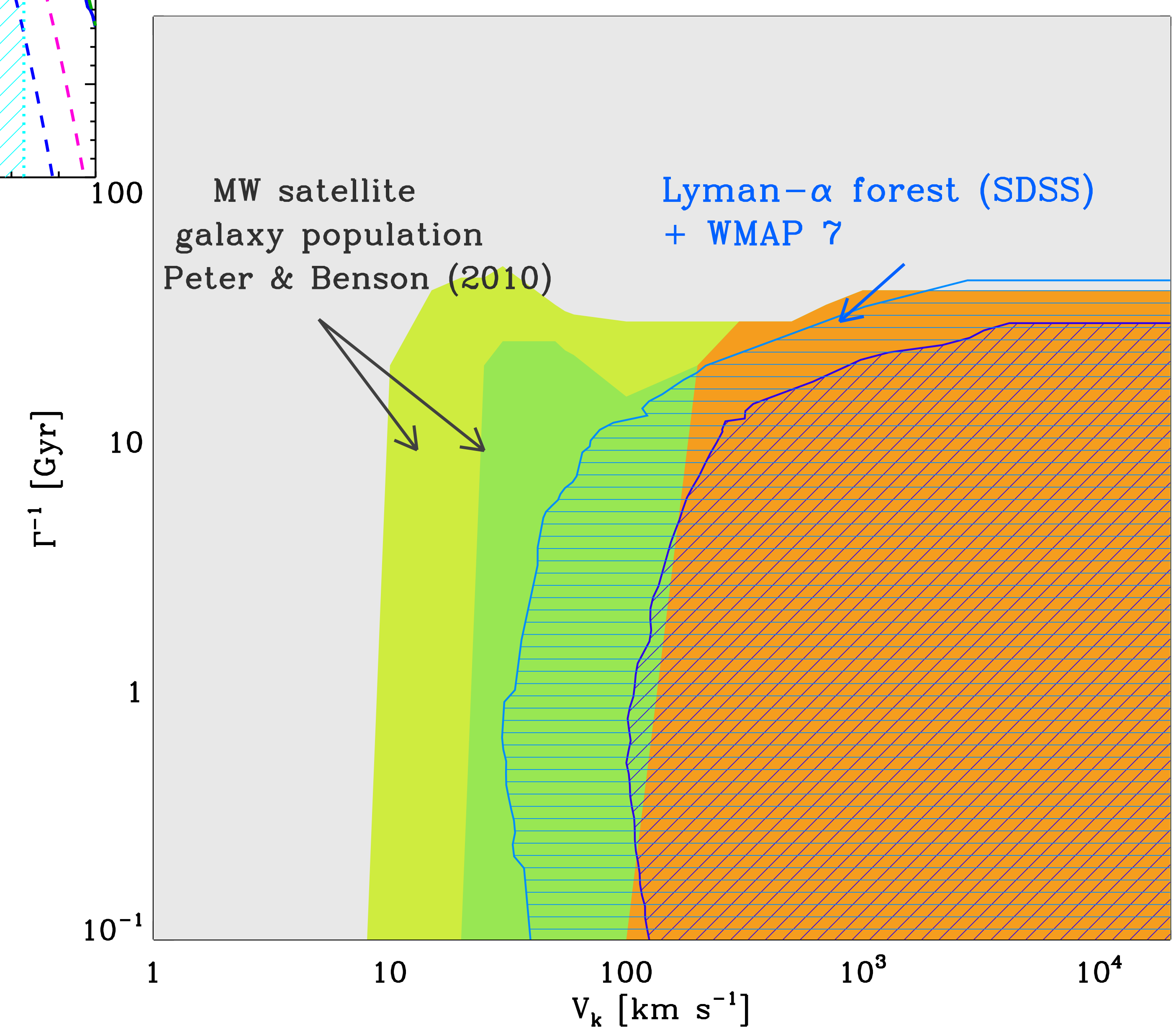
Wang and Zentner, PRD, 2012



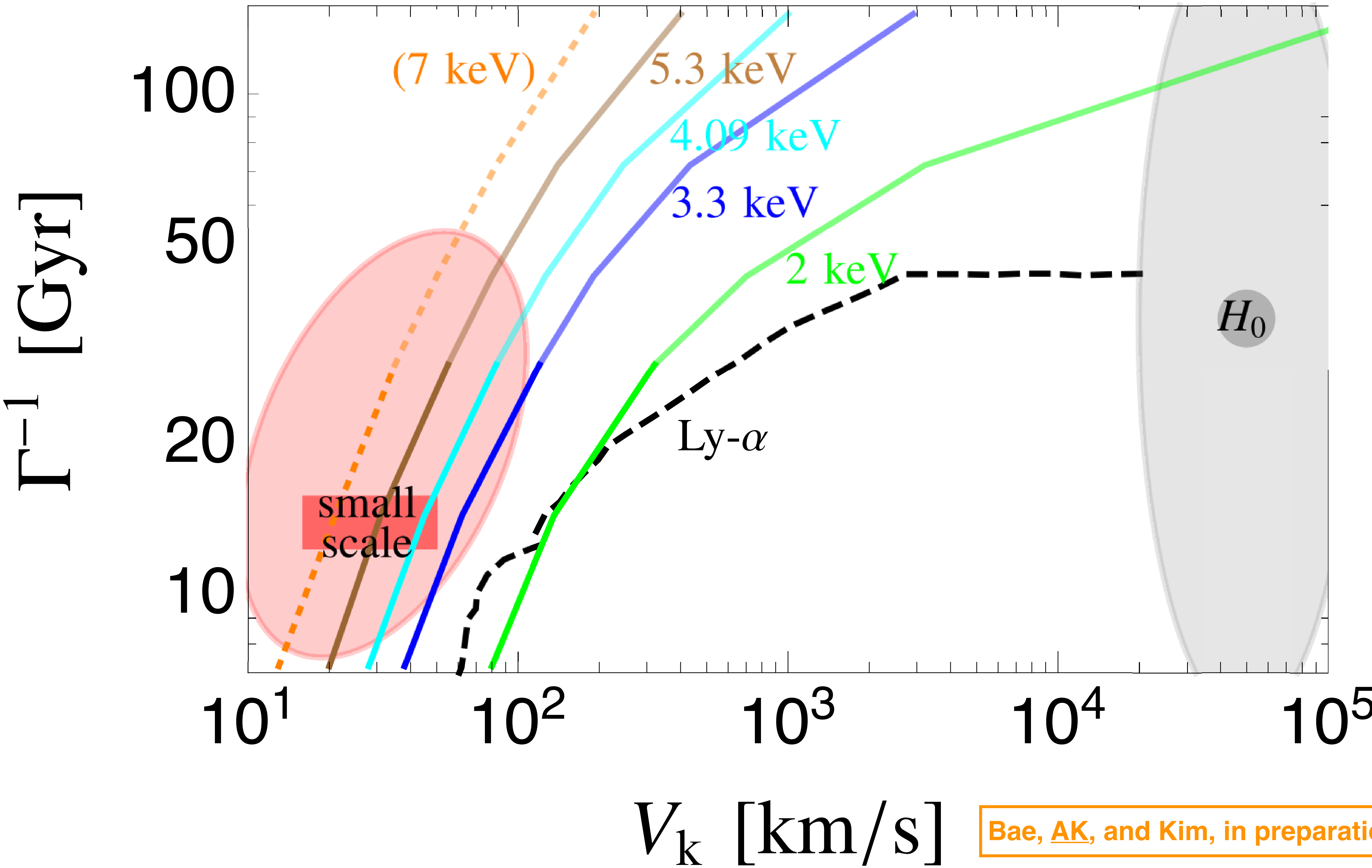
Lyman-α forest



Wang *et al.*, PRD, 2013



Lyman-α forest



Bae, AK, and Kim, in preparation

Small-scale structure

Possible discrepancies from the CDM (WIMPs) prediction on galactic (sub-Mpc) scales (small-scale issues)

Bullock and Boylan-Kolchin, ARAA, 2018

Issues may be attributed to incomplete understanding of complex astrophysical processes (subgrid physics)

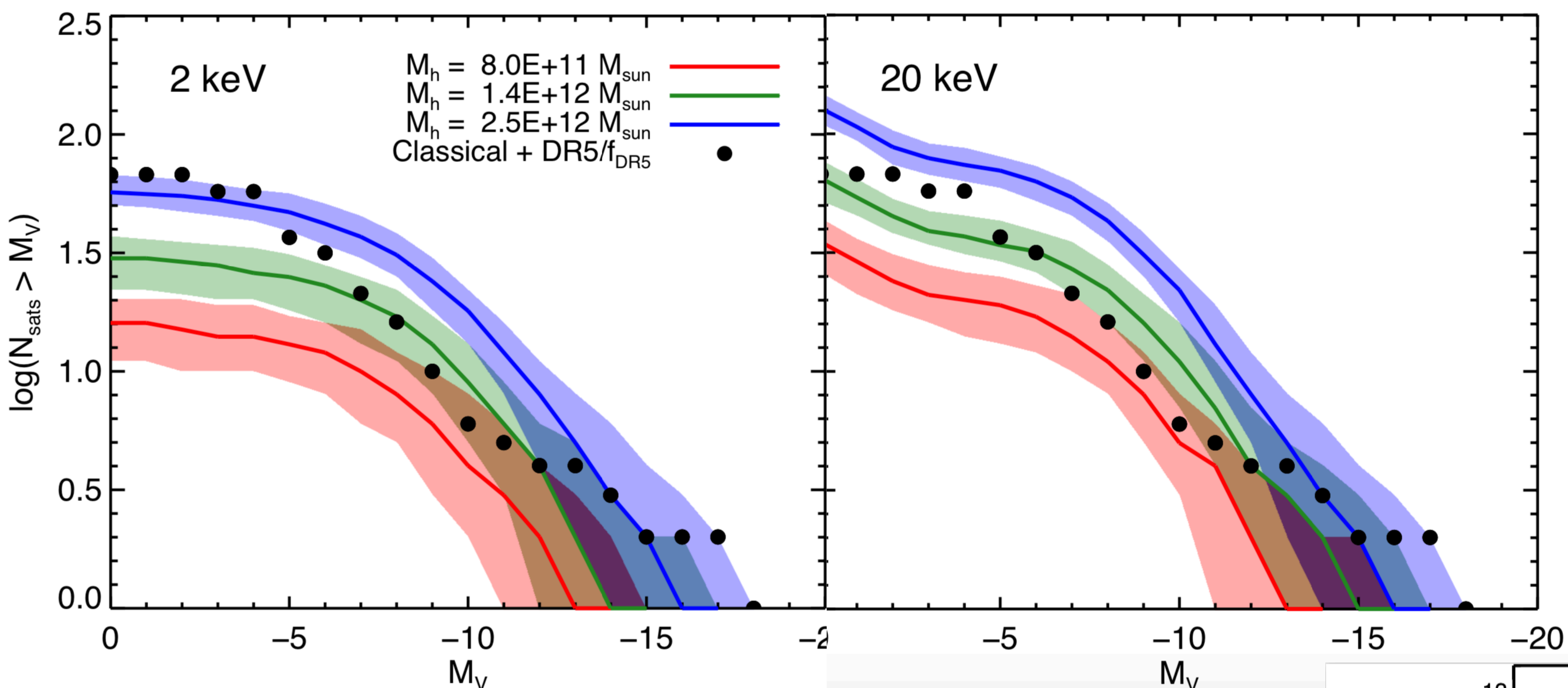
APSOTLE collaboration, MNRAS, 2016 | NIHAO collaboration, MNRAS, 2016 | FIRE cllaboration, ApJ, 2016

- gas heating from ionizing photons

- mass loss by supernova explosions

Rapidly developing hydrodynamic simulations are going to reach consensus on impacts of astrophysical processes

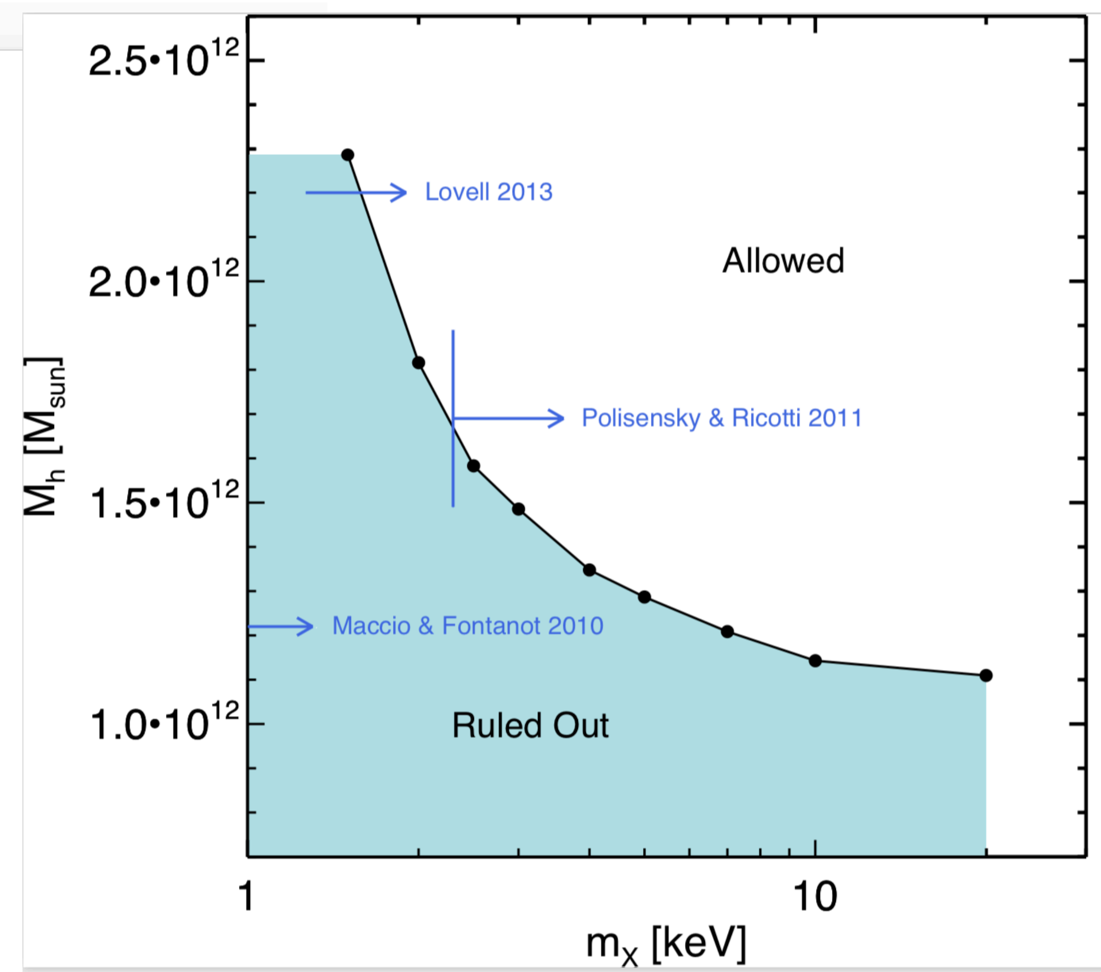
Missing satellite problem w/ WDM



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

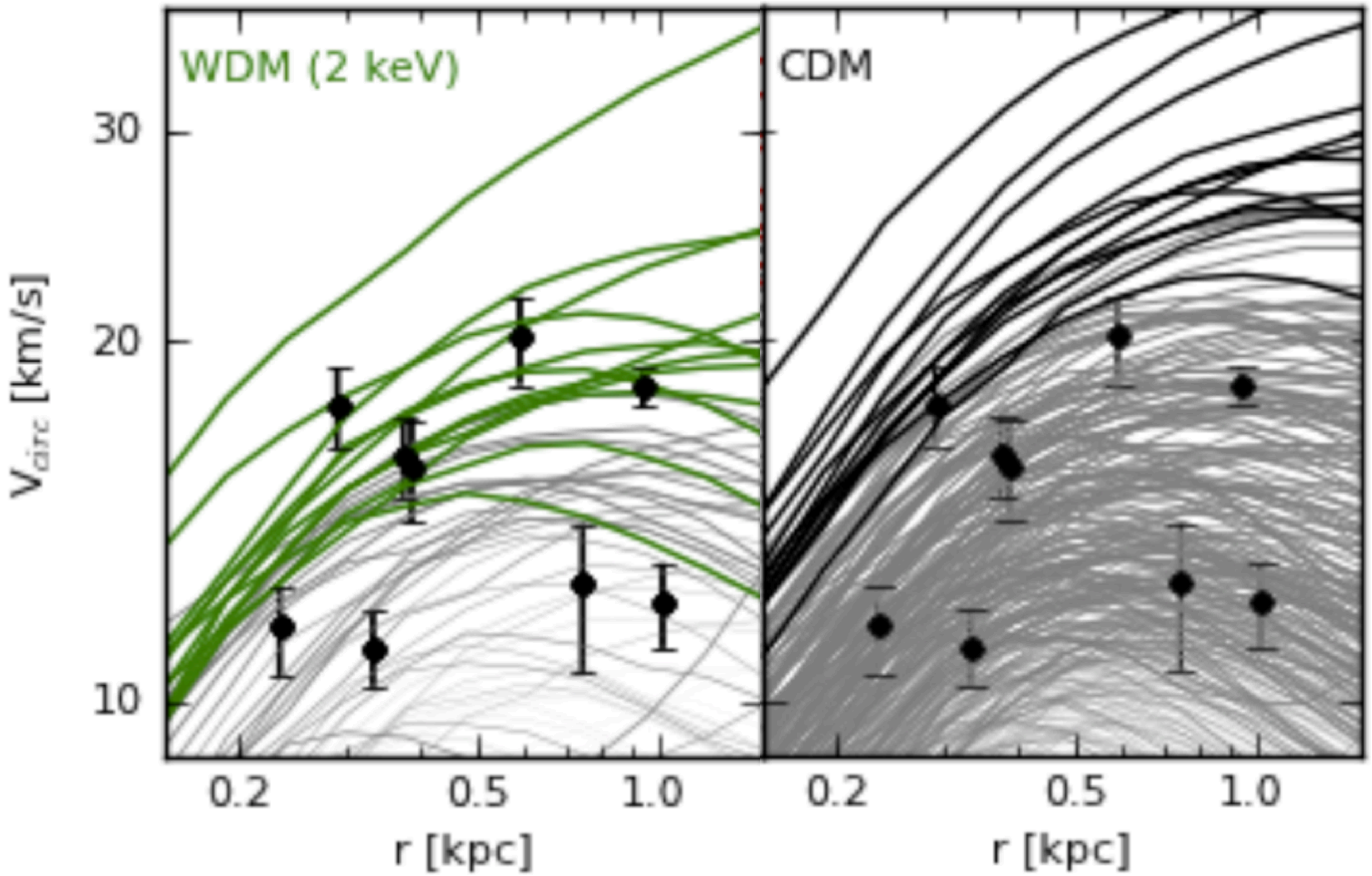
WDM reduces a predicted number of satellite galaxies

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



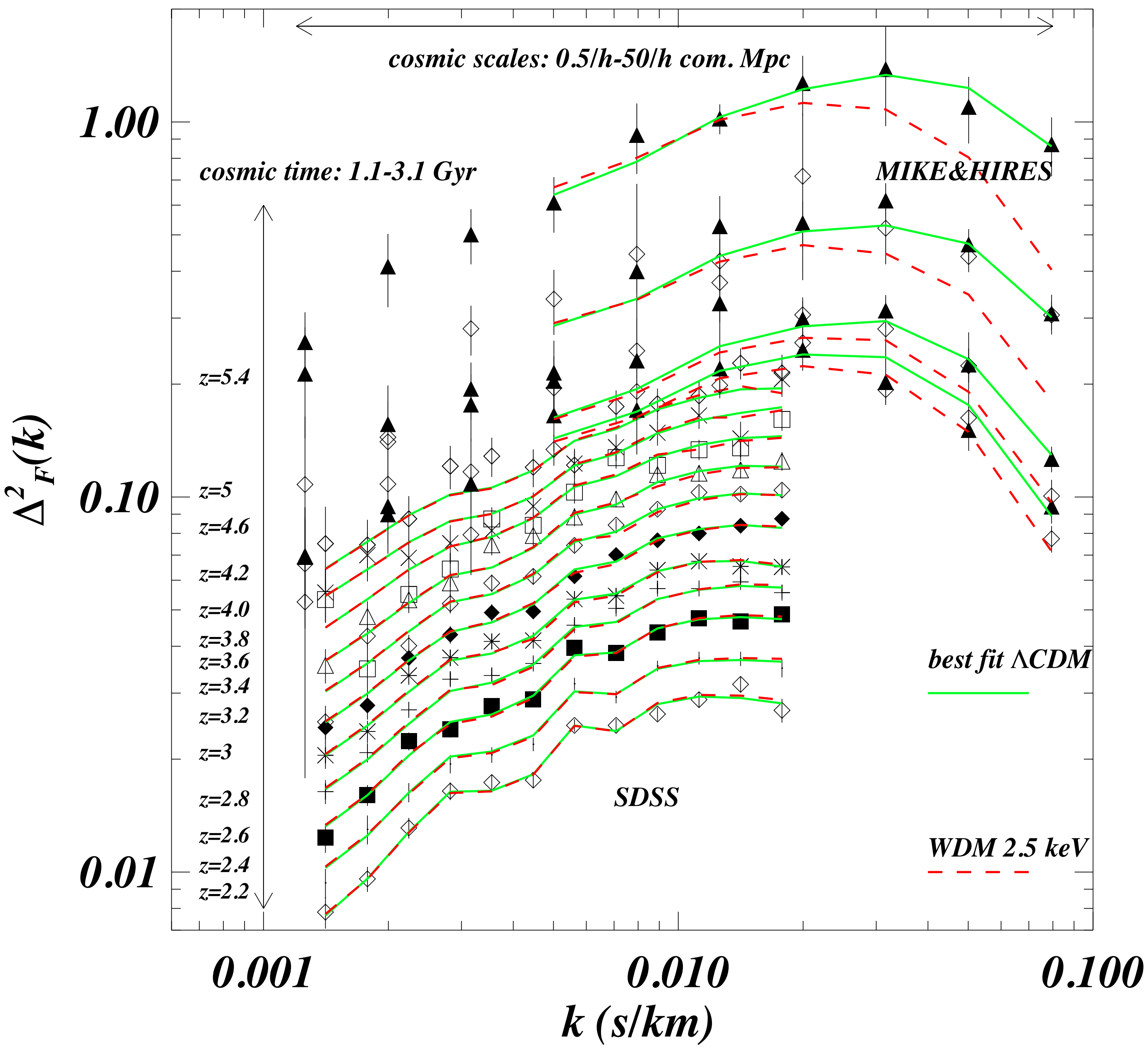
Too-big-to-fail problem w/ WDM

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



WDM reduces a predicted number of bigger subhalos than observed satellites

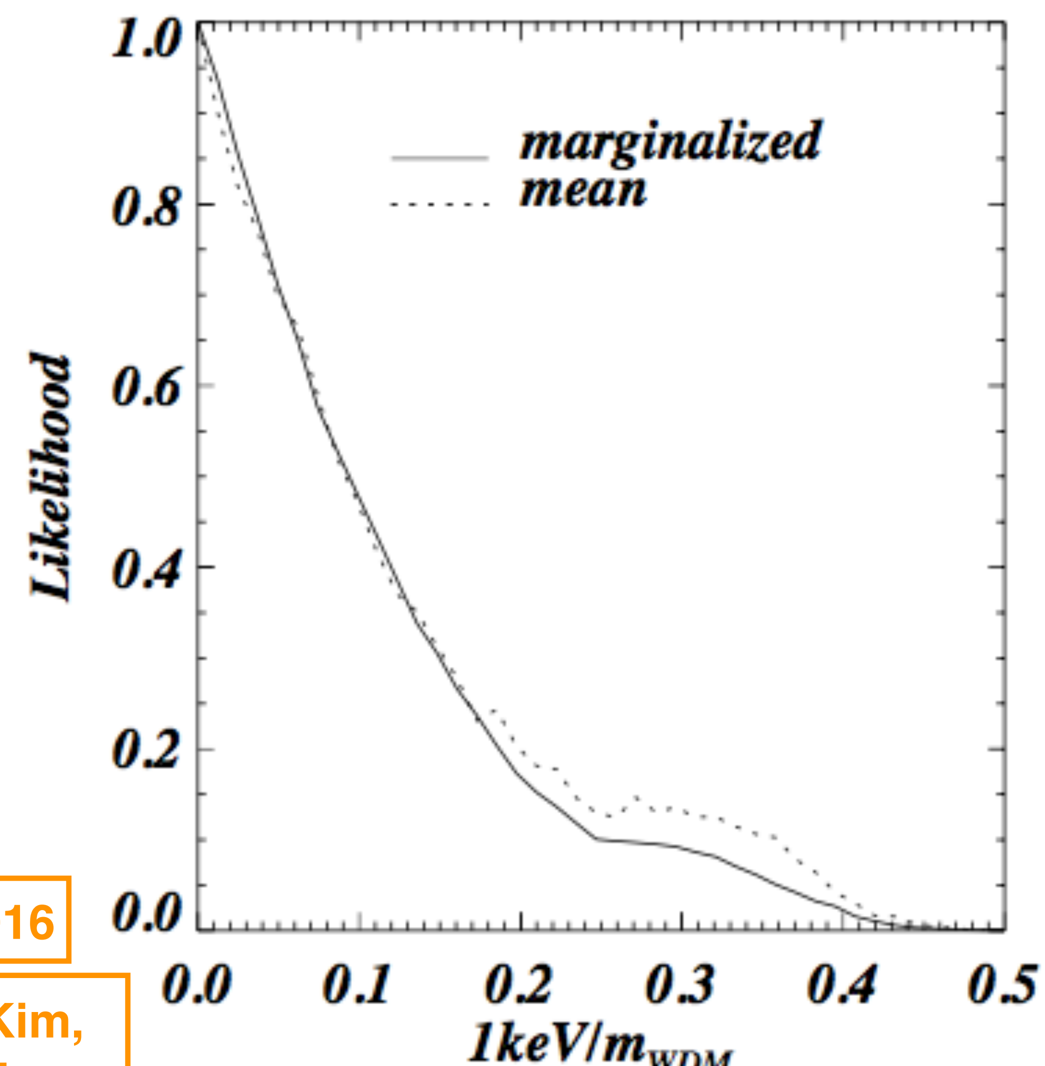
Lyman-α forest constraints on WDM



Viel, Becker, Bolton, and Haehnelt, PRD, 2013

WDM suppresses clumping of neutral hydrogen probed by Lyman-α forest in high-z quasar spectra

→ $m_{\rm WDM} \gtrsim 3.3\,{\rm keV}$



c.f., $m_{\rm WDM} \gtrsim 2.0, 4.09, 5.3\,{\rm keV}$

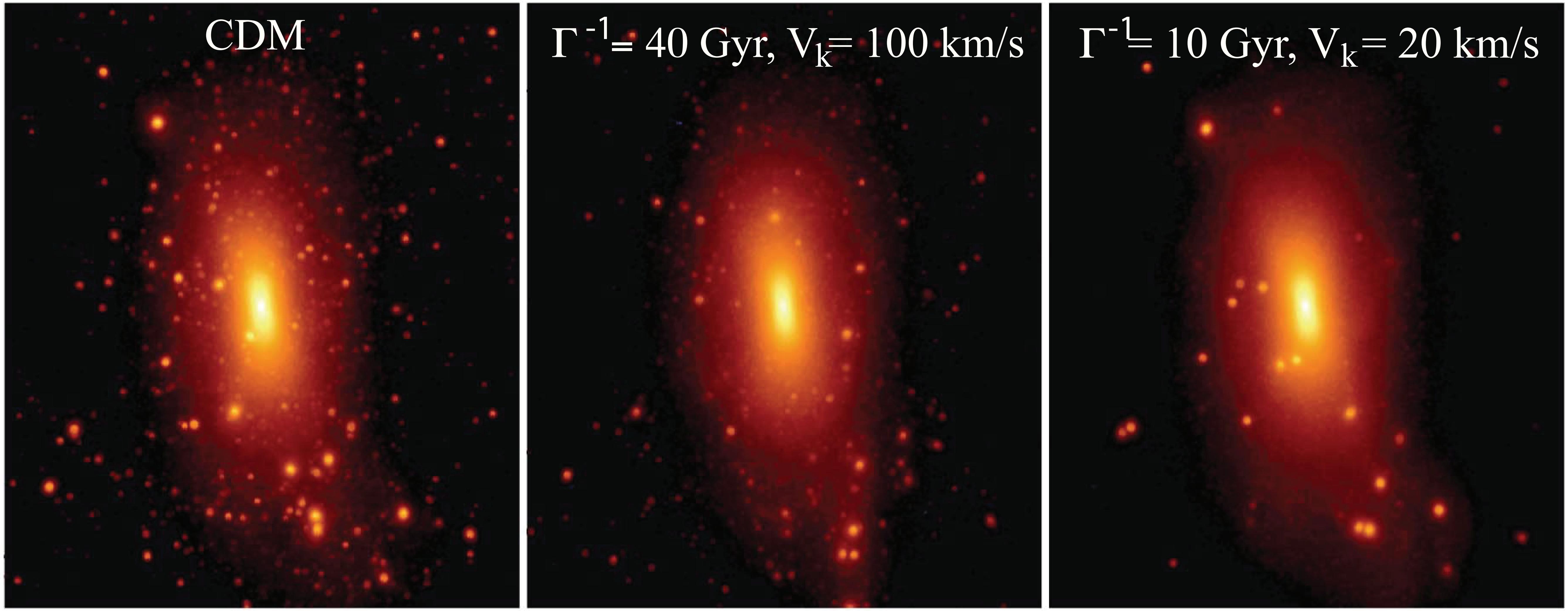
Viel, Lesgourgues, Haehnelt, Matarrese, and Riotto, PRD, 2005

Baur, Palanque-Delabrouille, Yèche, Magneville, and Viel, JCAP, 2016

Iršič, Viel, Haehnelt, Bolton, Cristiani, Becker, D'Odorico, Cupani, Kim, Berg, López, Ellison, Christensen, Denny, and Worseck, PRD, 2017

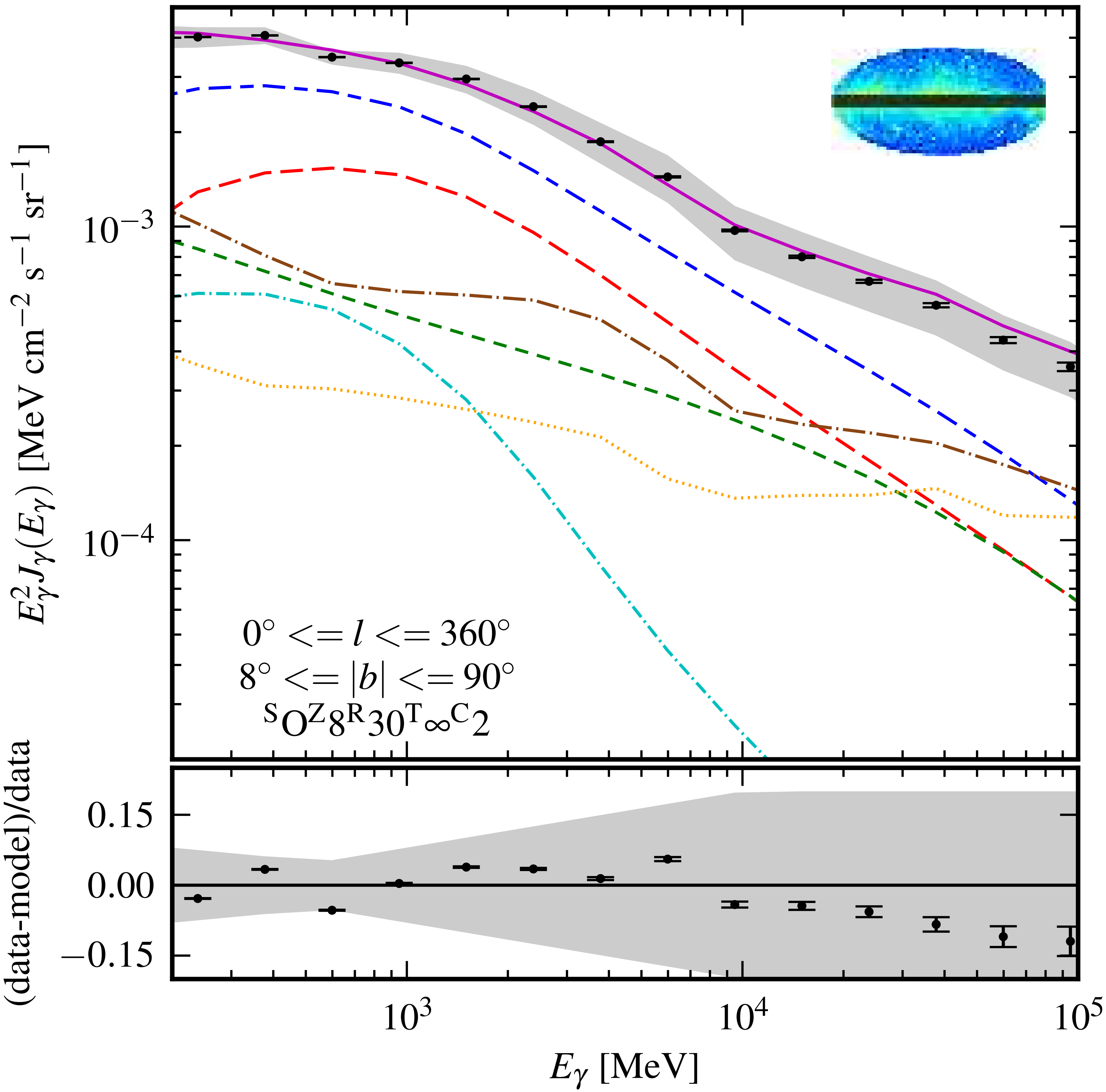
Halo structure

Wang *et al.*, PRD, 2014



Gamma-ray

Fermi-LAT collaboration, ApJ, 2012

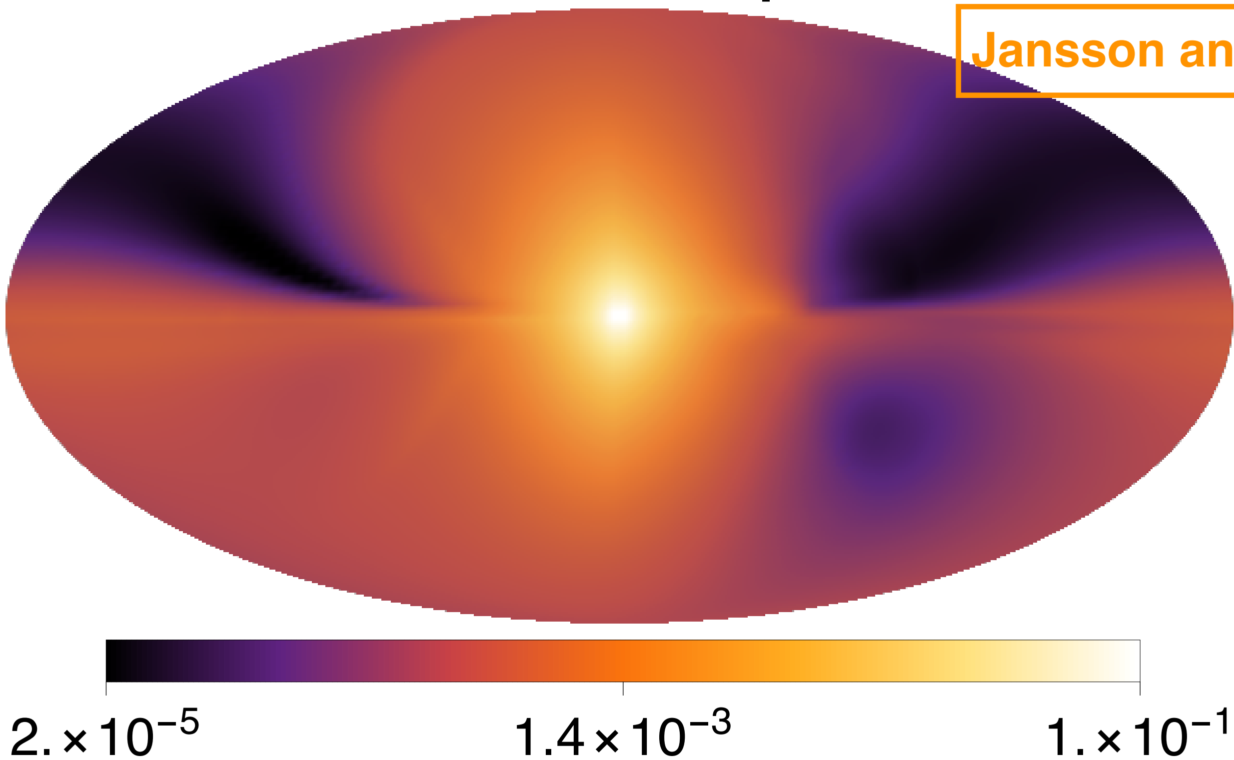


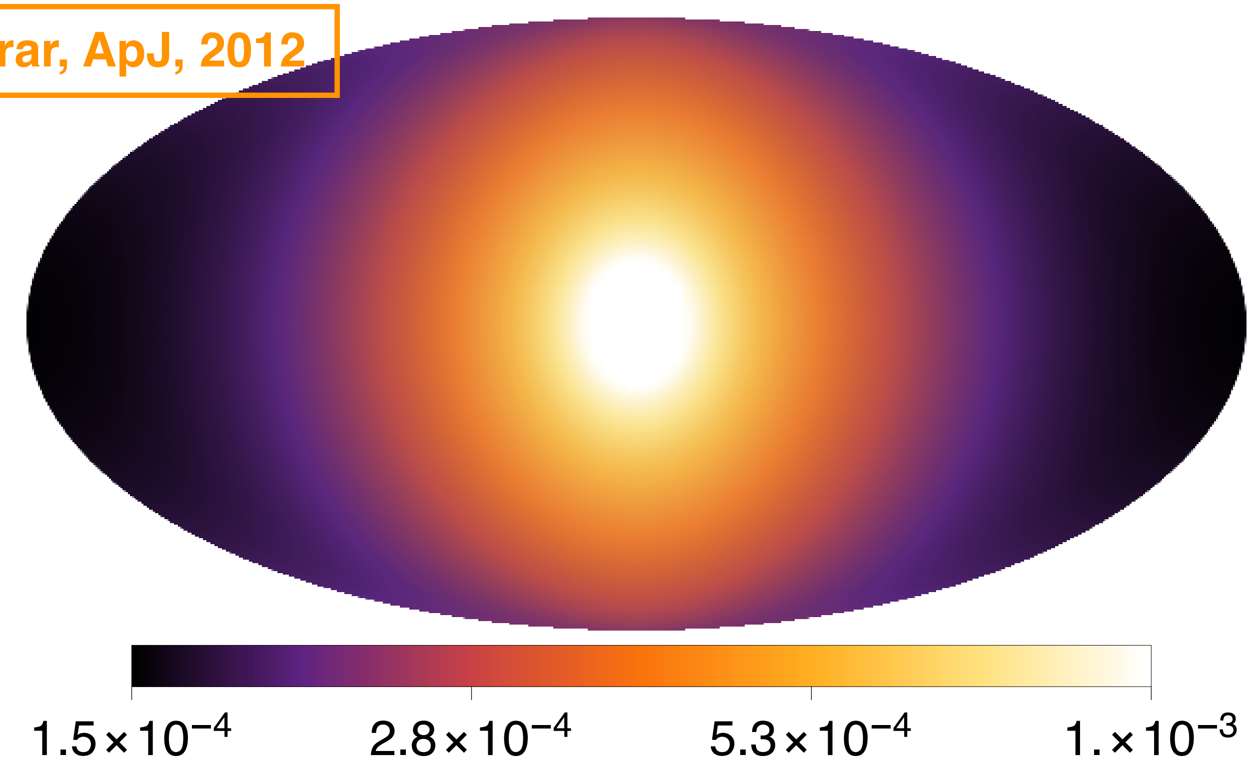
Different Galactic magnetic field model

Bae, AK, and Kim, PRD, 2019

disk + toroidal + poloidal halo

Jansson and Farrar, ApJ, 2012





axi-symmetric spiral disk + toroidal halo

Pshirkov *et al.*, ApJ, 2011

bi-symmetric spiral disk + toroidal halo