Sudden kinetic decoupling of dark matter

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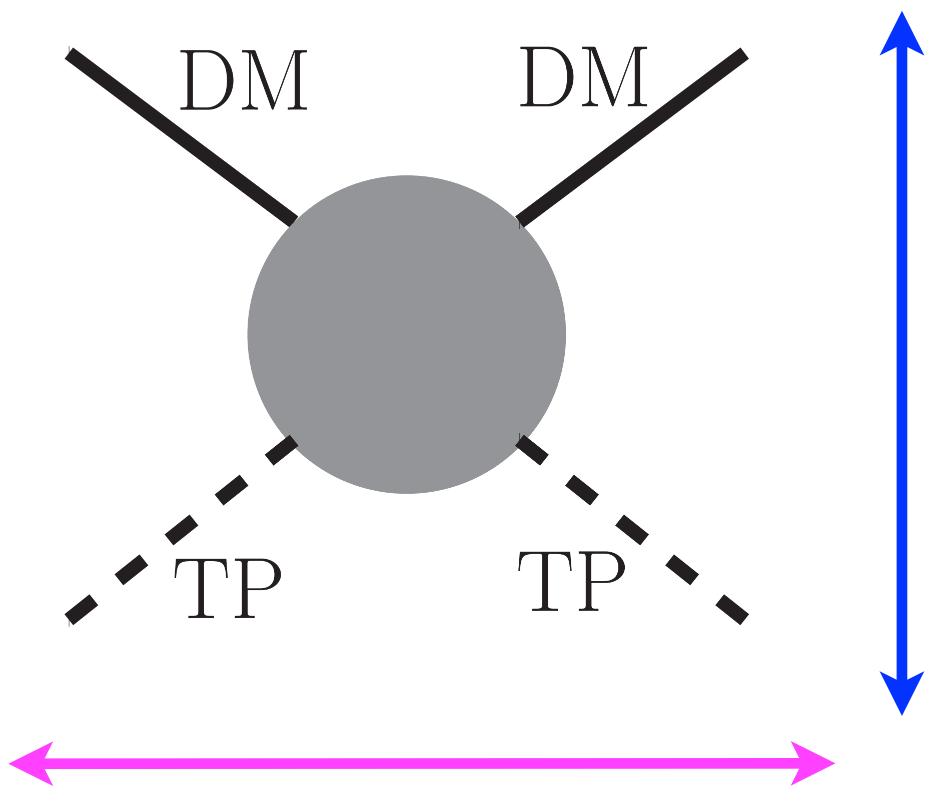
Based on
T. Binder, L. Covi, AK, H. Murayama, T. Takahashi, N. Yoshida, JCAP, 2016
AK, K. Kohri, T. Takahashi, N. Yoshida, PRD, 2016
AK, T. Takahashi. arXiv:1703.02338

see also talks by Pyungwon Ko & Joern Kersten

Jul. 12, 2017 @ DSU

DM-thermal bath interaction



: **chemical interaction**
the number of DM is NOT conserved.
the energy&momentum of DM are redistributed.

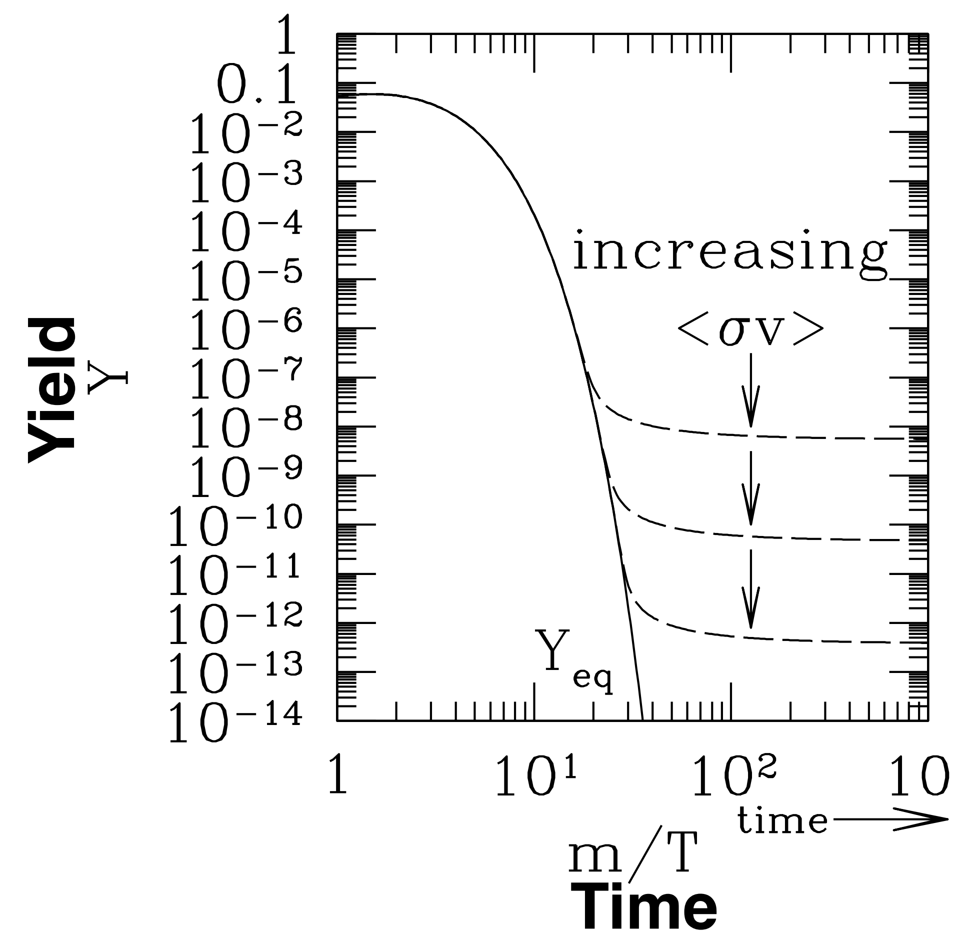
→ **At the chemical decoupling, the number density of DM freezes out.**

→ **Observational consequence: relic abundance of DM**

: **kinetic interaction**
the number of DM is conserved.
the energy&momentum of DM are redistributed.

→ **After the kinetic decoupling, DM streams freely.**

→ **Observational consequence: minimum mass of protohalo**



Fokker-Planck approximation

It is computationally challenging to follow the momentum redistribution through the kinetic interaction

Boltzmann equation:

$$\underbrace{\left[P^\mu \partial_{x^\mu} - \Gamma^\mu_{\kappa\lambda} P^\kappa P^\lambda \partial_{P^\mu}\right] f}_{\text{well-established}} = \underbrace{C[f]}_{\text{hard to deal with}}$$

well-established

hard to deal with

Ma *et al.*, ApJ, 1995

Bringmann *et al.*, JCAP, 2007 | **Bringmann, New J. Phys, 2009**

Bertschinger, PRD, 2006 | **Gondolo *et al.*, PRD, 2012**

T. Binder, L. Covi, AK, H. Murayama, T. Takahashi, N. Yoshida, JCAP, 2016

Fokker-Planck approximation:
expanding the collision term w.r.t. $q/p \ll 1$
i.e., the momentum change per collision q
$\ll$ the typical DM momentum p

Fokker-Planck equation

$$C[f_{\rm DM}] = m_{\rm DM}\frac{\partial}{\partial \mathbf{p}_{{\rm DM}i}}\left[\gamma\left(m_{\rm DM}T\frac{\partial f_{\rm DM}}{\partial \mathbf{p}_{{\rm DM}i}} + (\mathbf{p}_{{\rm DM}i} - m_{\rm DM}\mathbf{u}_i)f_{\rm DM}\right)\right]$$

differential cross section MODEL-INDEPENDENT!

$$\gamma = \frac{1}{6m_{\rm DM}T}\sum_{s_{\rm TP}}\int\frac{d^3\mathbf{p}_{\rm TP}}{(2\pi)^3}f^{\rm eq}_{\rm TP}(1\mp f^{\rm eq}_{\rm TP})\int^0_{-4\mathbf{p}^2_{\rm TP}}dt(-t)\frac{d\sigma}{dt}v$$

thermal momentum squared $\propto p^2$ **momentum transfer squared** $\propto q^2$

Gondolo *et al.*, PRD, 2012

T. Binder, L. Covi, AK, H. Murayama, T. Takahashi, N. Yoshida, JCAP, 2016

T : temperature
$u^\mu(x)$: bulk velocity
of thermal bath plasma

Homogeneous and isotropic solution:
Maxwell-Boltzmann distribution $f_0 = \frac{\bar{n}}{g_\chi}\left(\frac{2\pi}{m_\chi T_{\chi 0}}\right)^{3/2}\exp\left(-\frac{\mathbf{q}^2}{2a^2 m_\chi T_{\chi 0}}\right)$

with $\frac{d\ln(a^2 T_{\chi 0})}{d\tau} = 2\gamma_0 a\left(\frac{T_0}{T_{\chi 0}} - 1\right)$

$\gamma/H > 1$ (coupled) → $T_{\chi 0} = T_0 \propto 1/a$

$\gamma/H < 1$ (decoupled) → $T_{\chi 0} \propto 1/a^2$

(with γ monotonically decreasing faster than $1/a$)

$\gamma/H = 1$
→kinetic decoupling temperature $T^{\rm kd}$

Waldstein *et al.*, PRD, 2017

DM perturbations

Fluid approximation - a closed set of equations

Ignoring the free streaming after the kinetic decoupling

Bertschinger, PRD, 2006

T. Binder, L. Covi, AK, H. Murayama, T. Takahashi, N. Yoshida, JCAP, 2016

DM fluid variables:

- δ : density perturbation
- θ : bulk velocity potential
- σ : anisotropic inertia
- π : entropy perturbation

DM sound speed:

$$c_\chi^2 = \frac{T_{\chi 0}}{m_\chi}\left(1 - \frac{1}{3}\frac{d\ln T_{\chi 0}}{d\ln a}\right)$$

Evolution equations (synchronous gauge)

/: for Perfect fluid

/: for Imperfect fluid

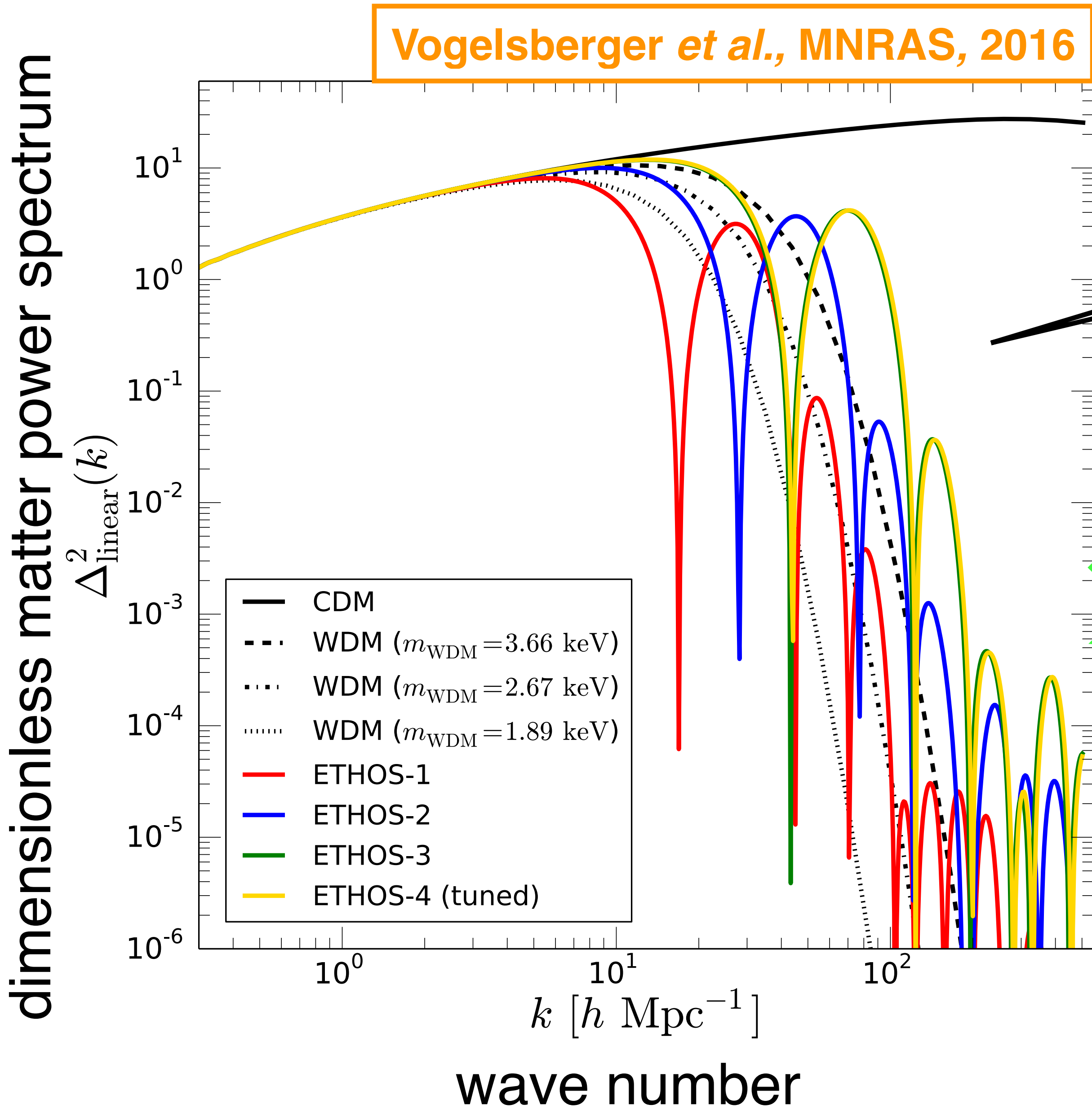
$$\dot{\delta} = -\theta - \frac{1}{2}\dot{h}$$

$$\dot{\theta} = -\frac{\dot{a}}{a}\theta - k^2\cancel{\sigma} + k^2(c_\chi^2\delta + \cancel{\pi}) + \gamma_0 a(\theta_{\rm TP} - \theta)$$

$$\dot{\sigma} = -2\frac{\dot{a}}{a}\sigma - k\left(\frac{2T_0}{m_\chi}\right)^{3/2}\left(\frac{21}{4}\cancel{f}_{03} + \cancel{f}_{11}\right) + \frac{4}{3}\frac{T_0}{m_\chi}\theta + \frac{2}{3}\frac{T_0}{m_\chi}(\dot{h} + 6\dot{\eta}) - 2\gamma_0 a\sigma$$

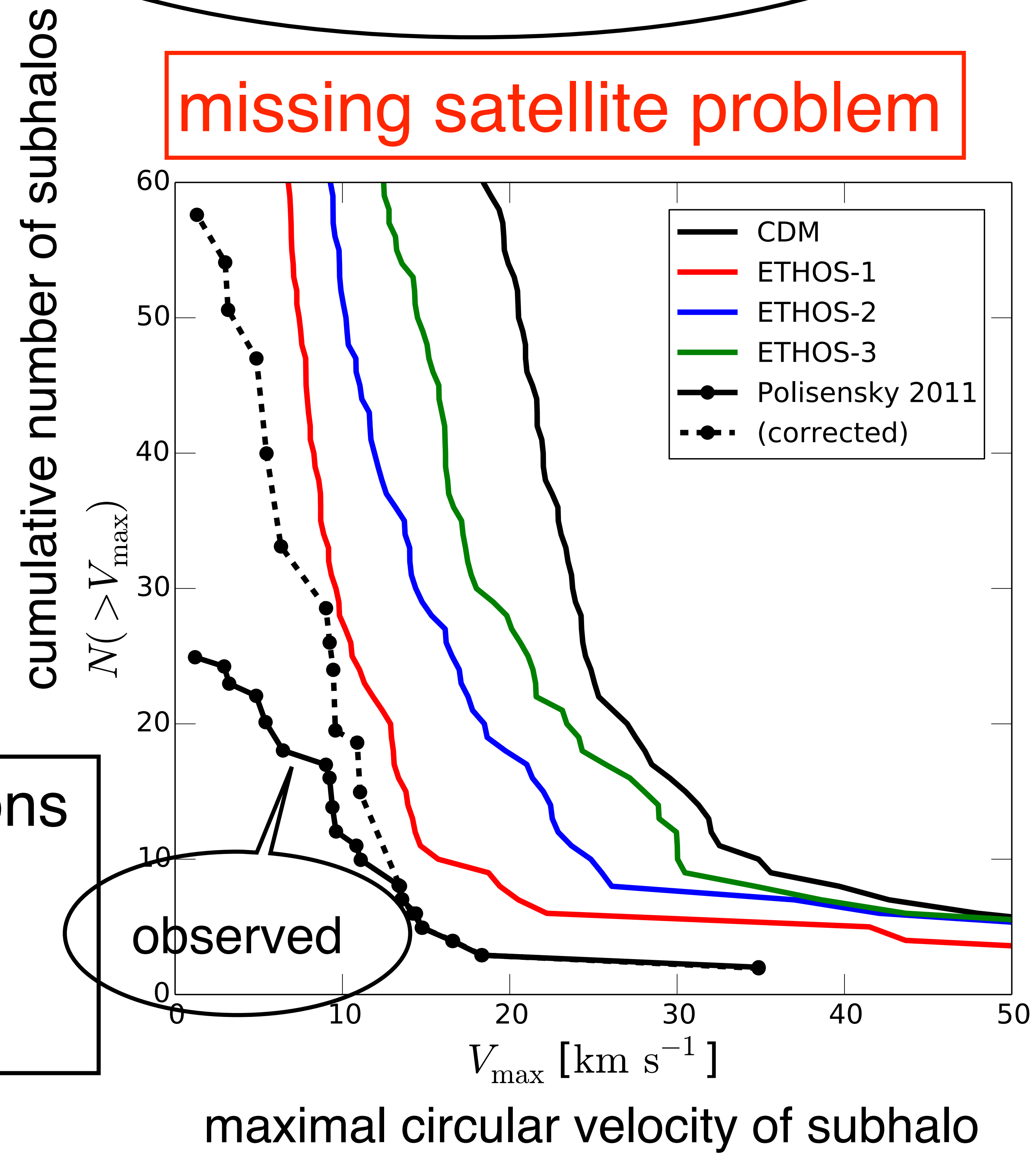
$$\dot{\pi} = -2\frac{\dot{a}}{a}\pi + \frac{5}{4}k\left(\frac{2T_0}{m_\chi}\right)^{3/2}\cancel{f}_{11} - \frac{1}{a^2}\frac{d(a^2c_\chi^2)}{d\tau}\delta - \left(\frac{5}{3}\frac{T_0}{m_\chi} - c_\chi^2\right)\theta - \frac{1}{2}\left(\frac{5}{3}\frac{T_{\chi 0}}{m_\chi} - c_\chi^2\right)\dot{h}$$
$$-2\gamma_0 a\left[\pi - \frac{T_1}{m_\chi} - \left(\frac{T_0}{m_\chi} - c_\chi^2\right)\delta\right] + 2\gamma_0 a\left(\frac{T_0}{T_{\chi 0}} - 1\right)\frac{T_{\chi 0}}{m_\chi}\frac{\gamma_1}{\gamma_0}$$

Implications for structure formation



oscillation scale $k_{\rm s}$: comoving sound horizon at the kinetic decoupling

missing satellite problem



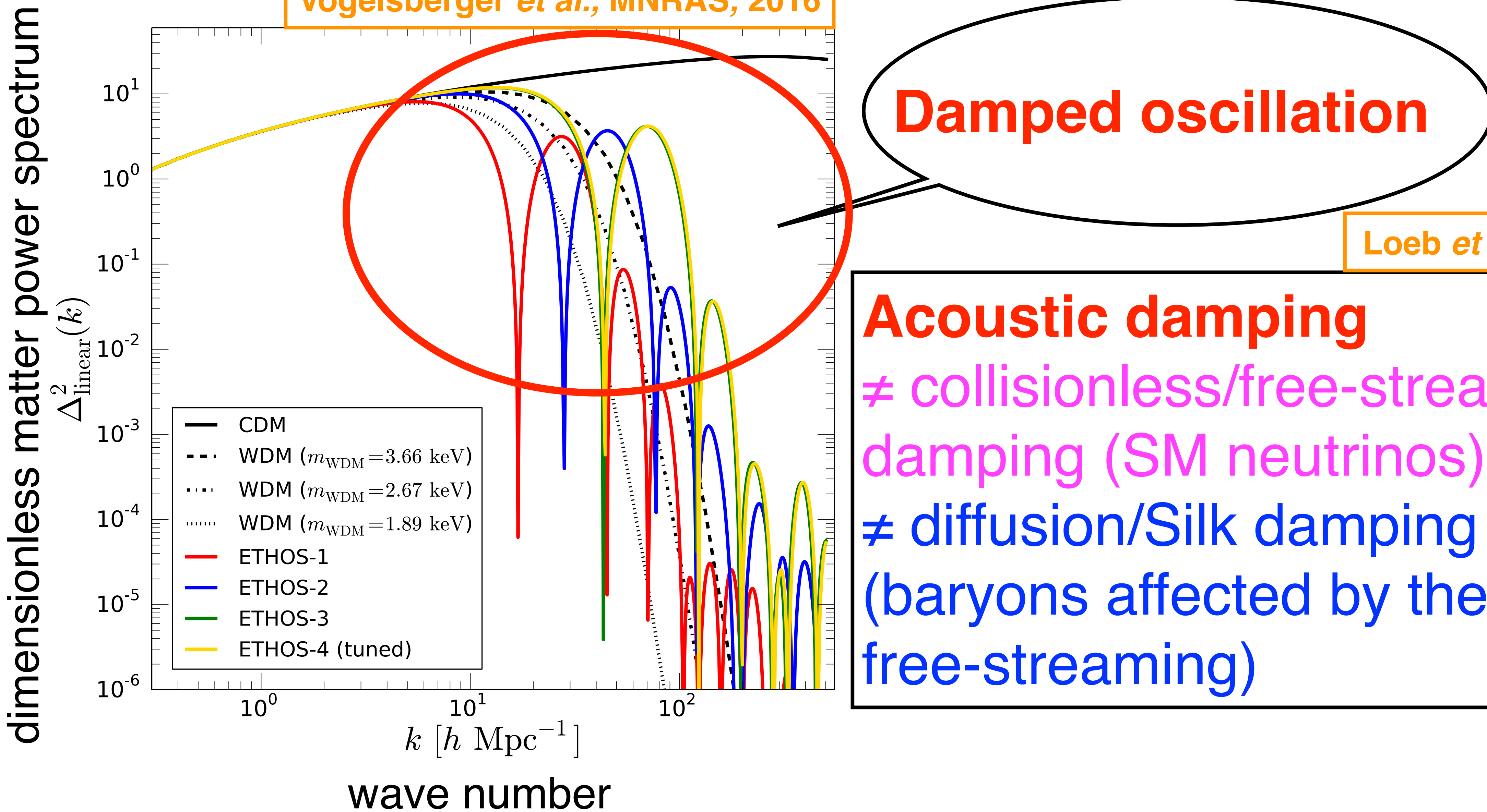
Suppressed matter density perturbations at galactic scales, $T^{\rm kd} = \mathcal{O}(1)\,{\rm keV}$
→ possible solution to the *small scale issues* in the standard CDM model

Question we have addressed

AK, K. Kohri, T. Takahashi, N. Yoshida, PRD, 2016

AK, T. Takahashi. arXiv:1703.02338

Vogelsberger *et al.*, MNRAS, 2016



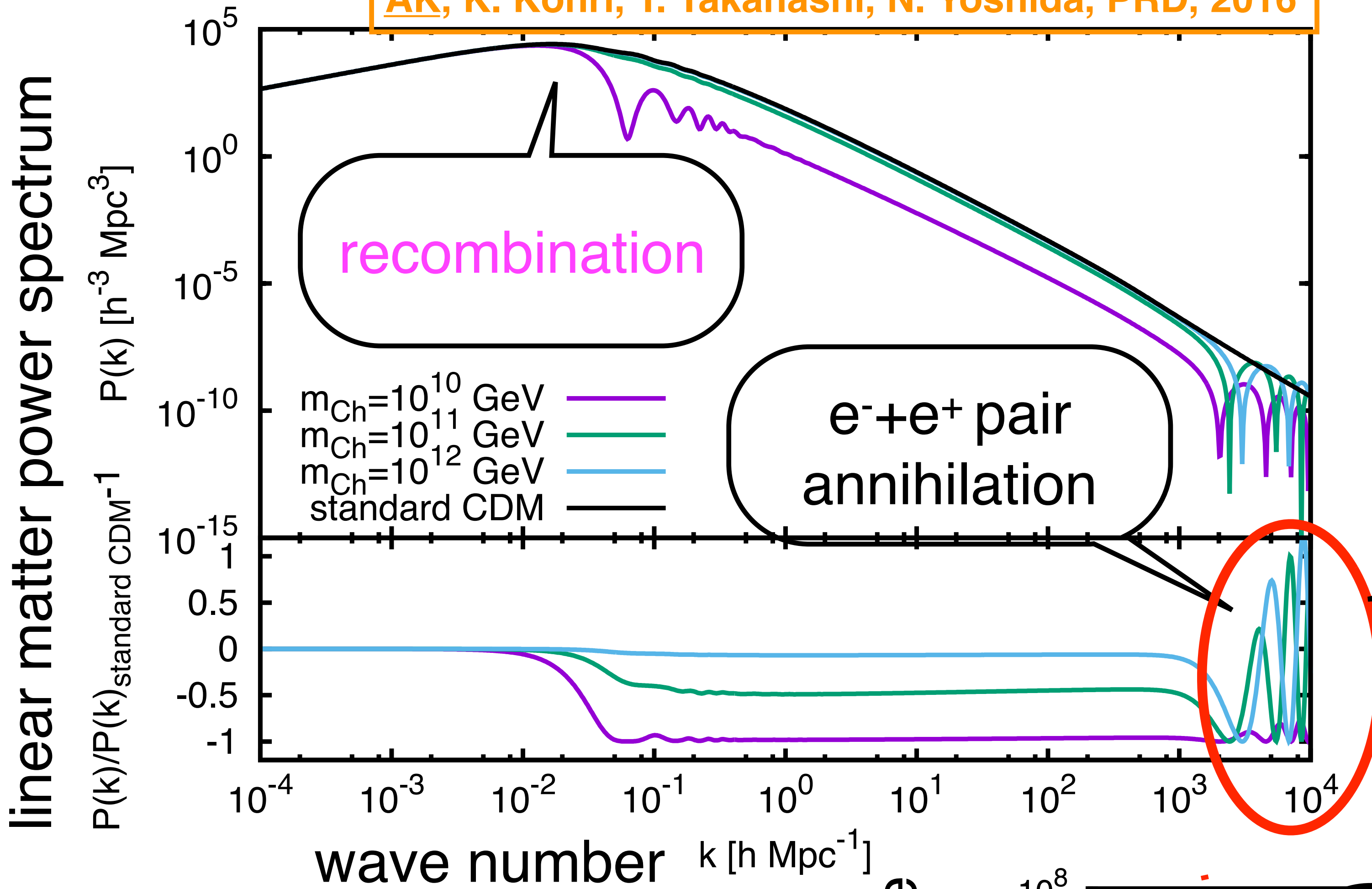
Loeb *et al.*, PRD, 2005

Acoustic damping
≠ collisionless/free-streaming damping (SM neutrinos)
≠ diffusion/Silk damping (baryons affected by the photon free-streaming)

What determines the damping scale?
- collisionless/free-streaming damping
→ free-streaming scale of DM
- diffusion/Silk damping
→free-streaming scale of radiation

Electrically charged DM

AK, K. Kohri, T. Takahashi, N. Yoshida, PRD, 2016

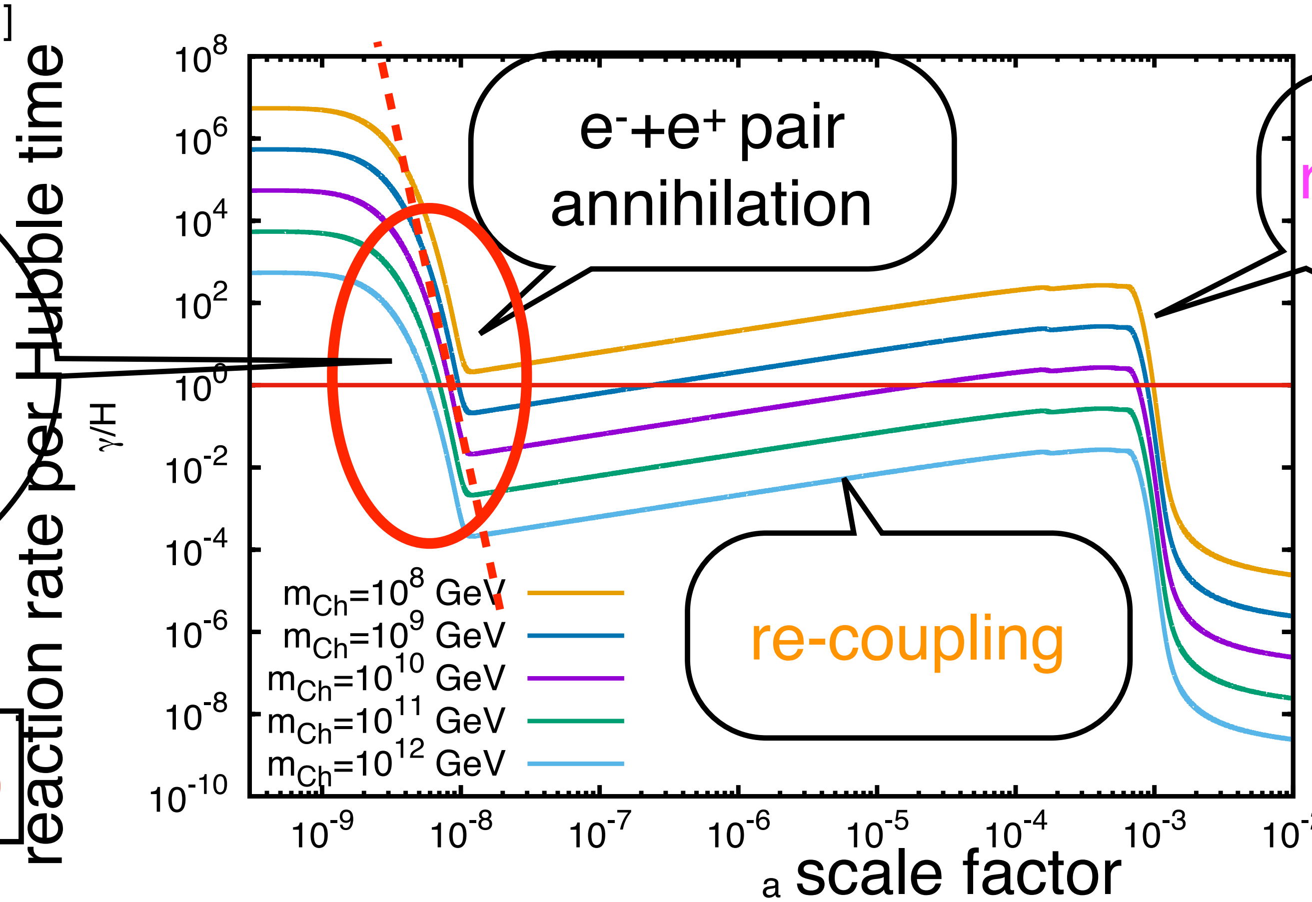


CHAMP
(CHArged Massive Particle)

Rujula *et al.*, Nucl. Phys B, 1990

Undamped oscillation!!

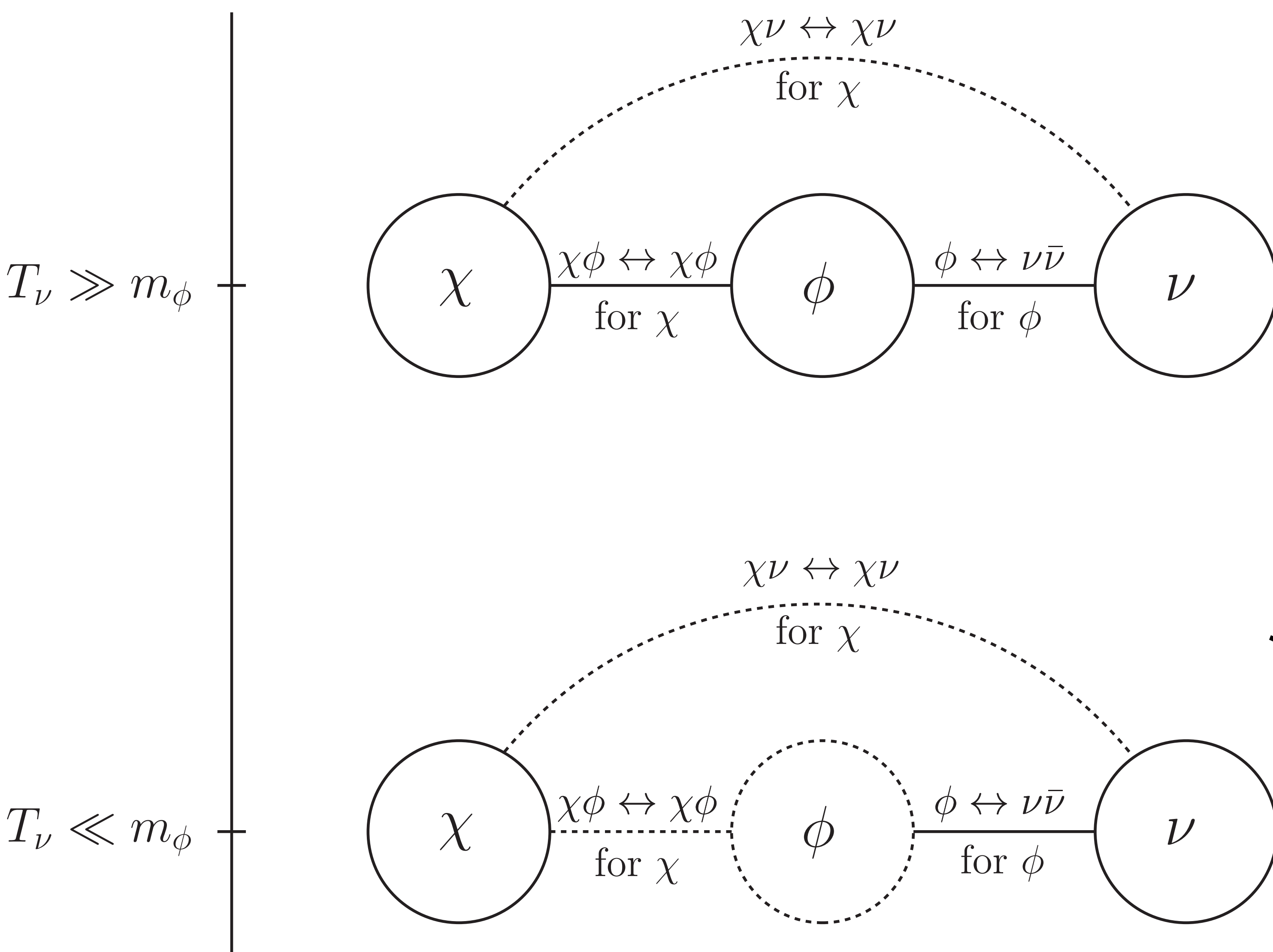
steep/sudden drop of γ/H at the kinetic decoupling (n~20)



$$\gamma/H \propto 1/a^{n+4} \quad (\gamma/H \approx 1)$$

Simplified realization

Suppose a simplified model, where SM is extended with DM fermion (χ) and light Dirac fermions (ν) coupled to a mediator boson (ϕ) $\quad r = T_\nu / T_\gamma$



AK, T. Takahashi. arXiv:1703.02338

$$\mathcal{L}_{\rm S} \supset g_\chi \bar{\chi}\phi\chi + g_\nu \bar{\nu}\phi\nu$$

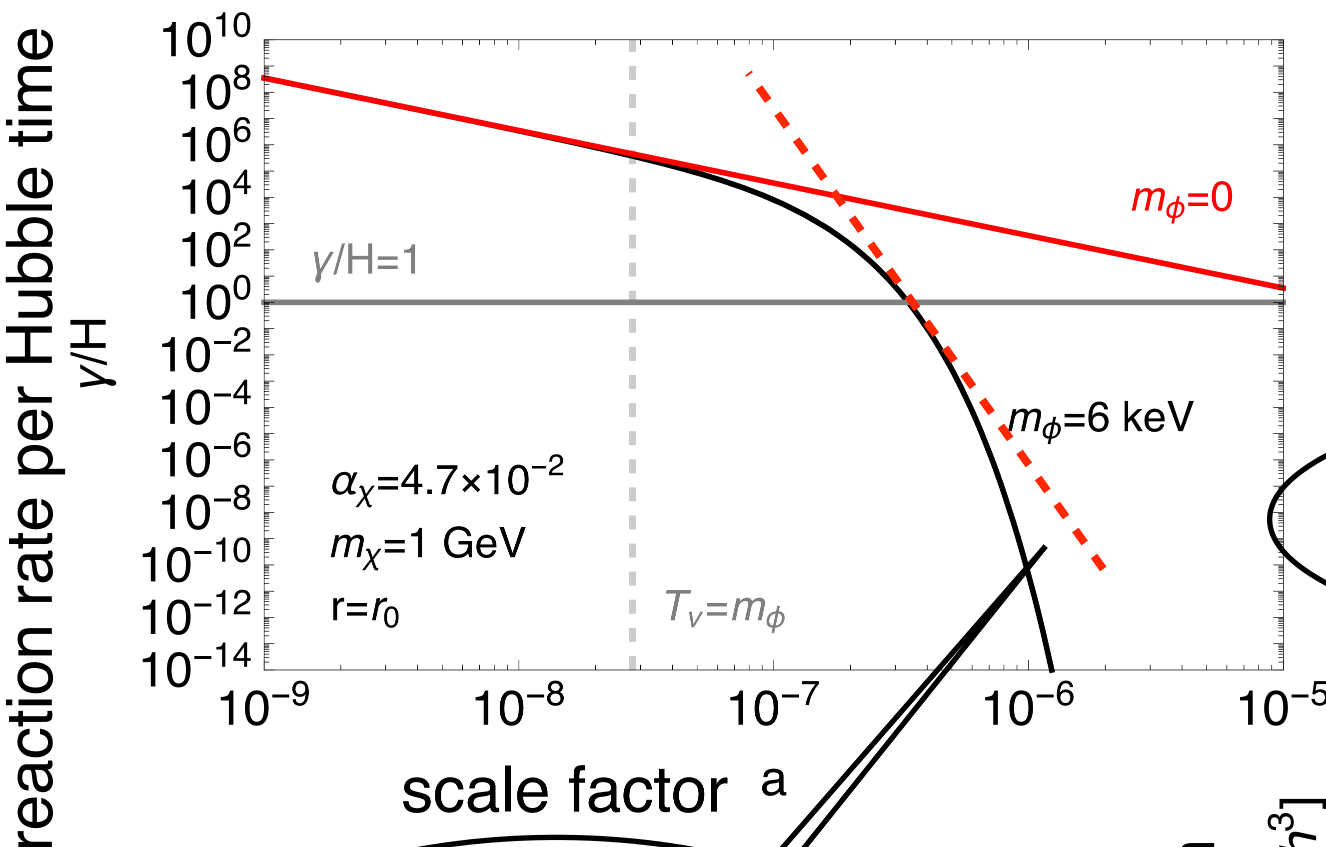
$$\mathcal{L}_{\rm V} \supset g_\chi \bar{\chi}\gamma^\mu\chi\phi_\mu + g_\nu \bar{\nu}\gamma^\mu\nu\phi_\mu$$

$$\mathcal{L}_{\rm PS} \supset i g_\chi \bar{\chi}\phi\gamma^5\chi + i g_\nu \bar{\nu}\phi\gamma^5\nu$$

$$\mathcal{L}_{\rm PV} \supset g_\chi \bar{\chi}\gamma^\mu\gamma^5\chi\phi_\mu + g_\nu \bar{\nu}\gamma^\mu\gamma^5\nu\phi_\mu$$

kinetic decoupling occurs when $T_\nu < m_\phi$ and thus $n_\phi \propto e^{-m_\phi/T_\nu}$

Reaction rate & resultant matter power spectra



χ : perfect fluid
ν : perfect fluid dark radiation

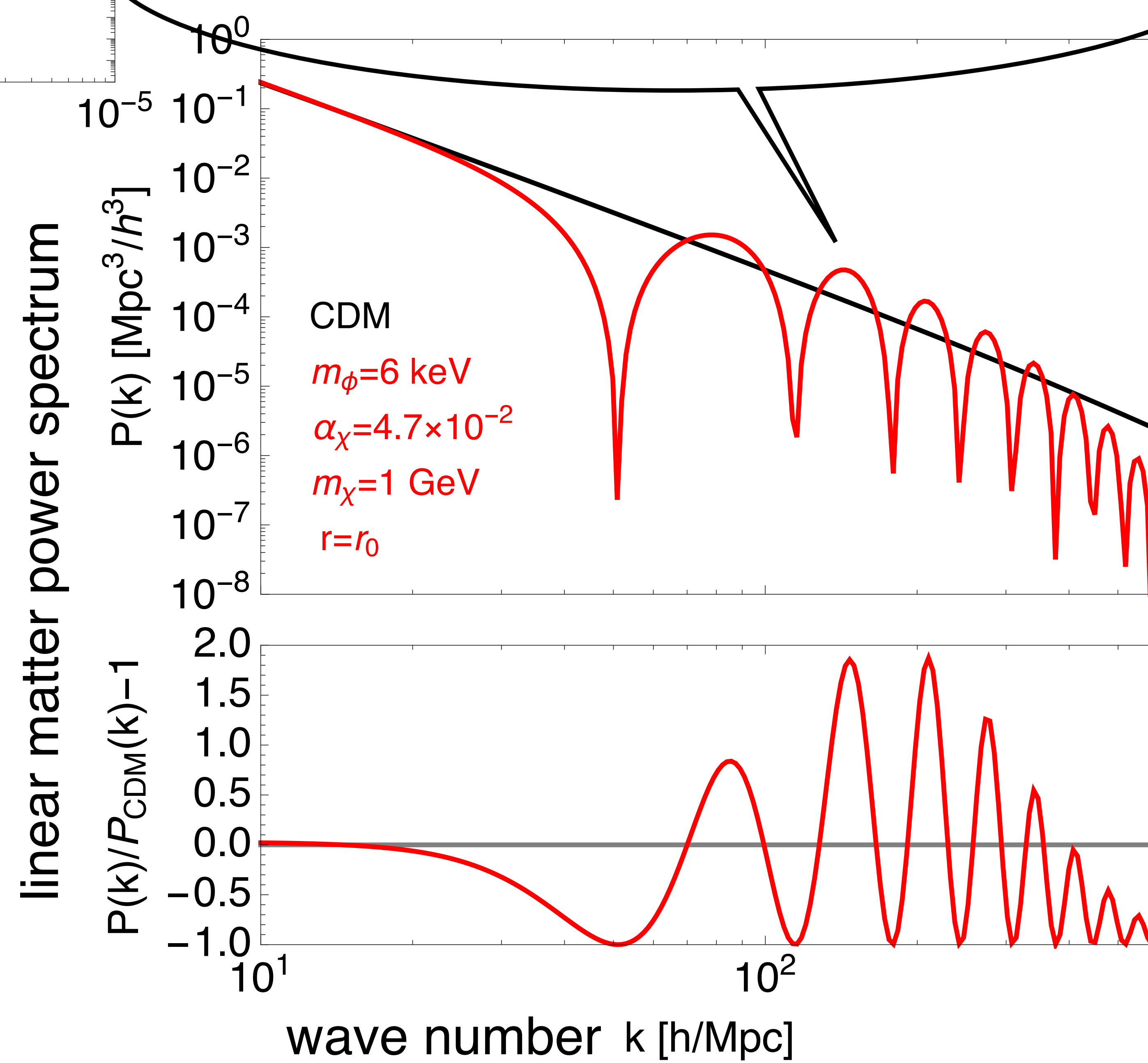
see the paper

AK, T. Takahashi. arXiv:1703.02338

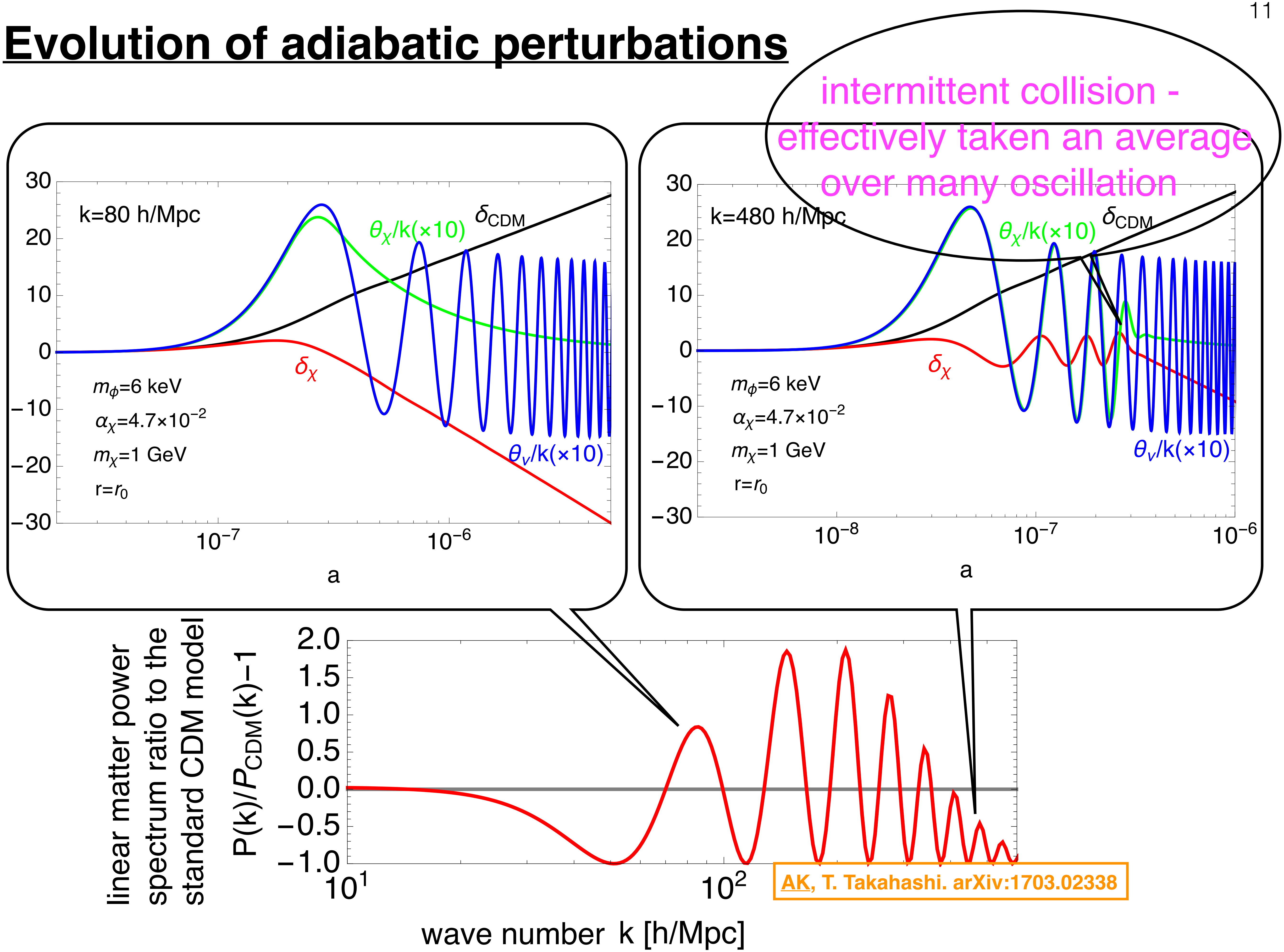
(Quasi-)undamped oscillation!!

steep/sudden drop of γ/H at the kinetic decoupling (n~10)

$$\gamma/H \propto 1/a^{n+4} \ (\gamma/H \approx 1)$$



Evolution of adiabatic perturbations



AK, T. Takahashi. arXiv:1703.02338

Damping scale

AK, T. Takahashi. arXiv:1703.02338

These observations infer the following **criterion for the damping scale** of dark acoustic oscillation:

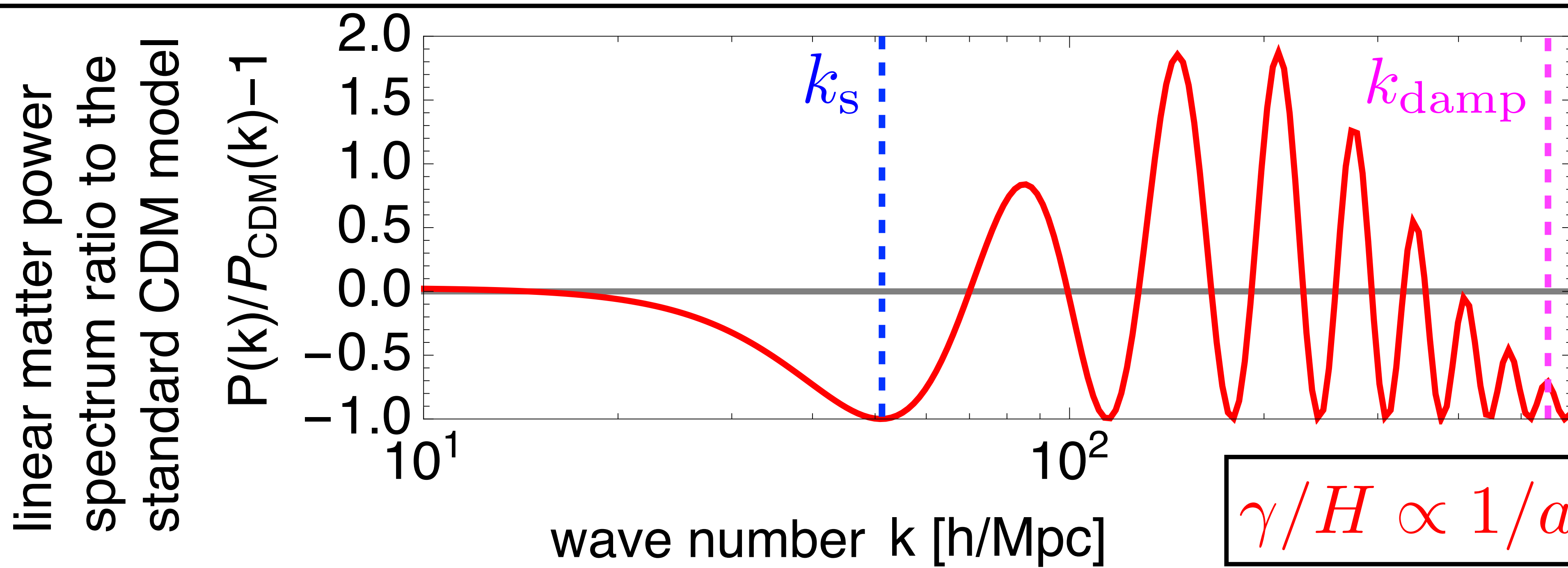
$$\frac{1}{\gamma_0/H}\left.\frac{d(\gamma_0/H)}{dt}\right|_{\gamma_0=H} = \frac{k_{\rm damp} c_{\rm s}}{a},$$

$c_{\rm s}$: sound speed of the plasma (usually $1/\sqrt{3}$)

(duration of the kinetic decoupling)$^{-1}$ (oscillation period)$^{-1}$

Analytical approaches (see the paper) implies $k_{\rm damp} = \frac{2(n+4)}{\pi} k_{\rm s}$ for $\gamma/H \propto 1/a^{n+4}$,

which is concordant with the above criterion (up to $2/\pi$)



(n~10)

$\boxed{\gamma/H \propto 1/a^{n+4} \ (\gamma/H \approx 1)}$

Summary and conclusion

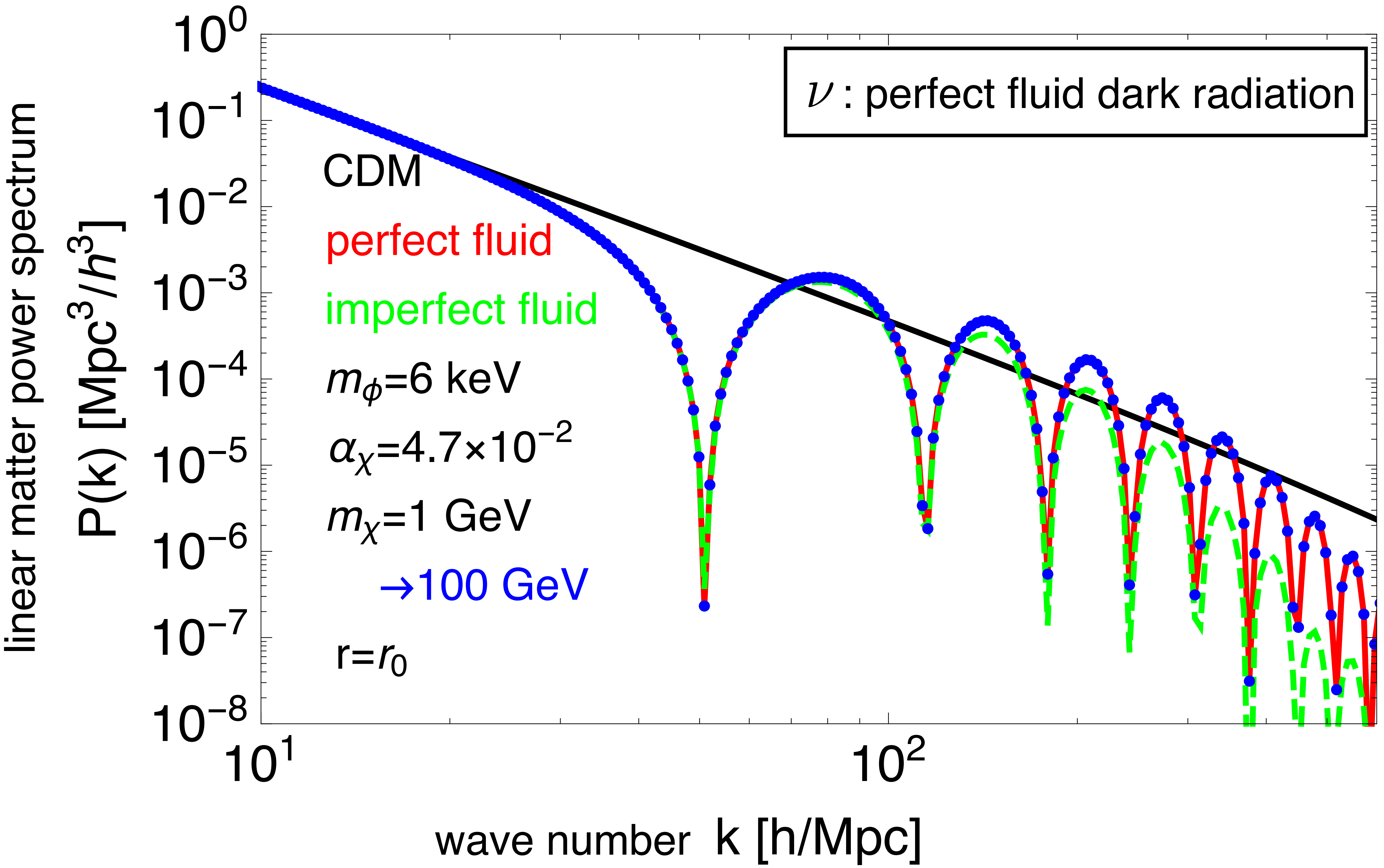
- Kinetic decoupling of DM leaves dark acoustic oscillation on the matter distribution of the Universe, which provides an invaluable hint on the nature of DM.

- The density perturbations at peak wavenumbers can be **larger** than those in the standard CDM model.
The damping scale is determined by equating the duration of the kinetic decoupling and acoustic oscillation period.

- Imprints of such enhanced dark acoustic oscillation on the non-linear matter distribution are worth investigating by performing *N*-body simulations in future work.

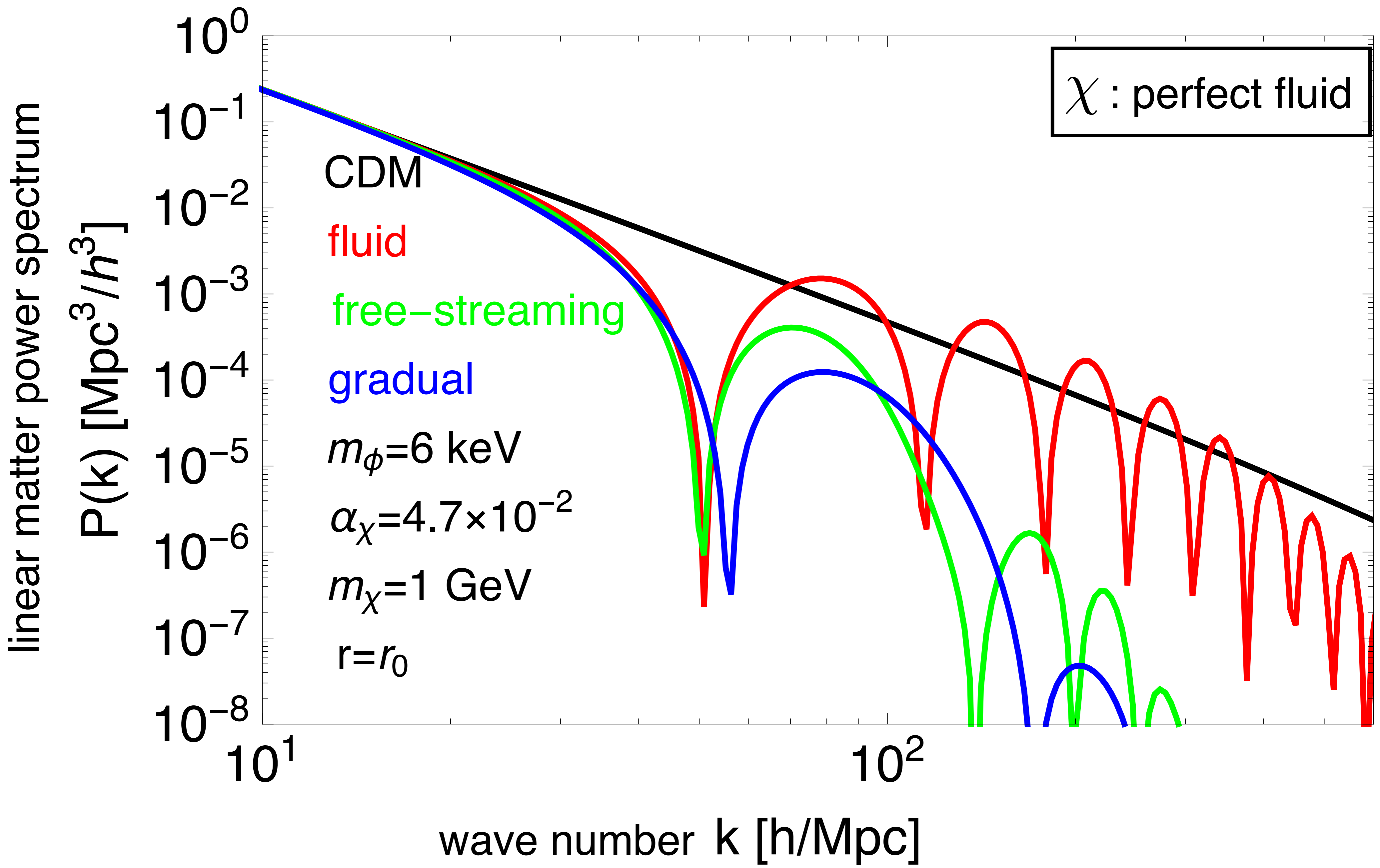
Backup slides

Effects of collisionless damping of DM



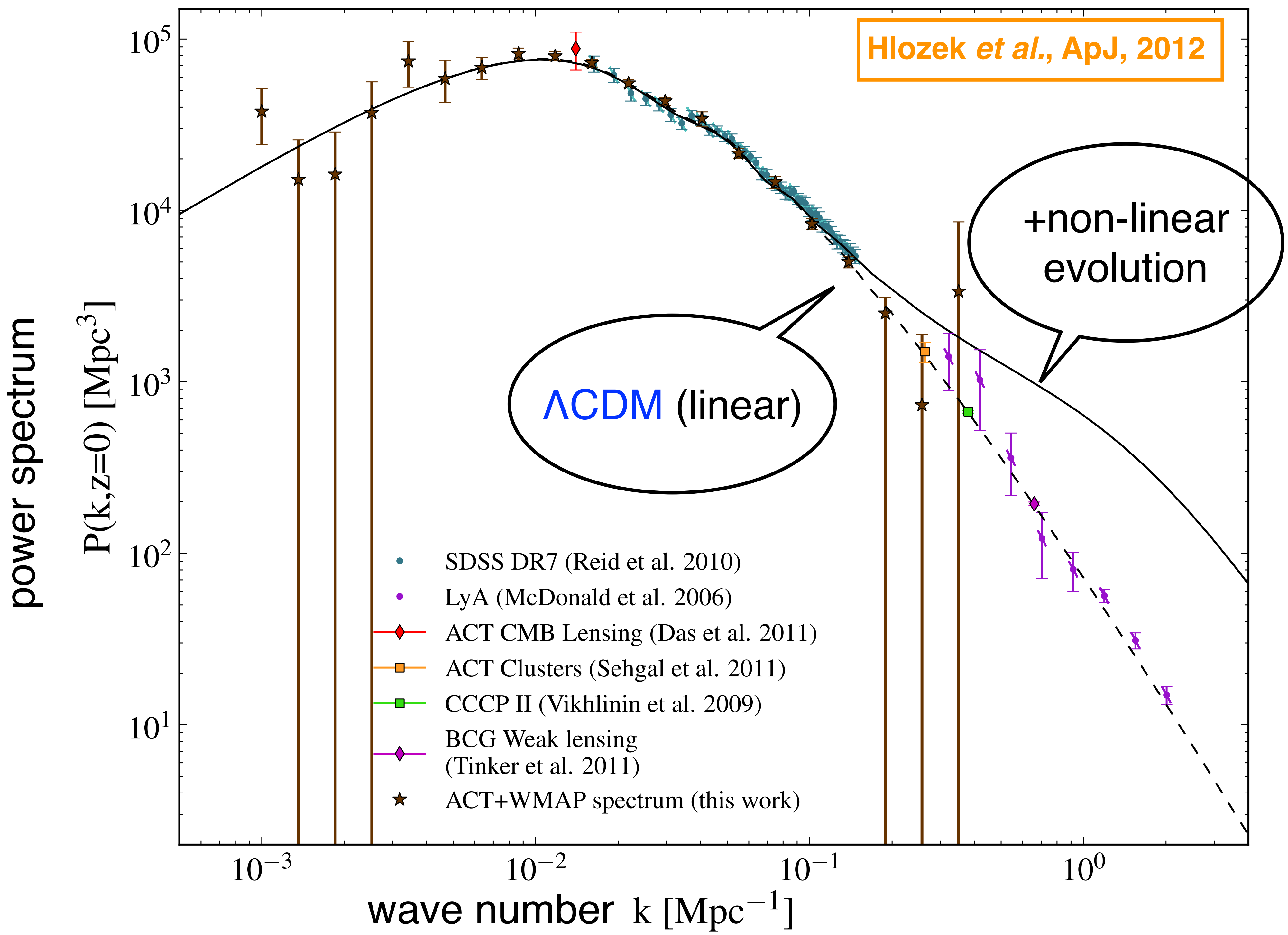
The collisionless damping of DM does not spoil the dark acoustic oscillation, but introduce an additional damping scale

Effects of collisionless damping of radiation



The collisionless damping of radiation completely changes the dark acoustic oscillation

Large scale structure of the Universe



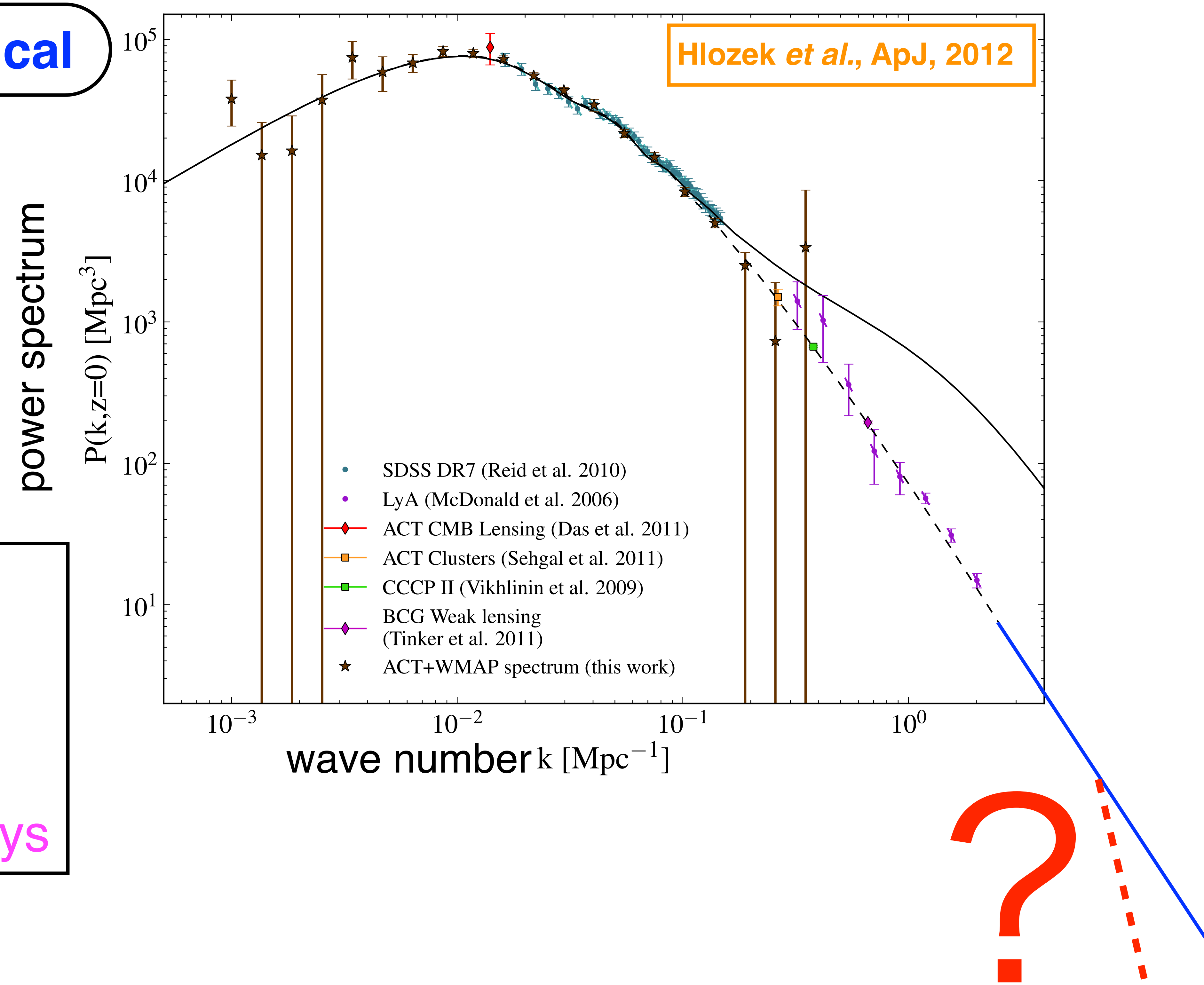
The ΛCDM model reproduces well
the large scale (>Mpc) structure of the Universe

Cold Dark Matter?

hypothetical

cold dark matter:
null thermal velocity
only gravitationally interacting

particle physics DM candidates:
finite (sizable) thermal velocity
interacting in many ways



Small scale matter density fluctuations, especially their deviations from the ΛCDM model, contain imprints of the nature of DM

Small scale crisis I

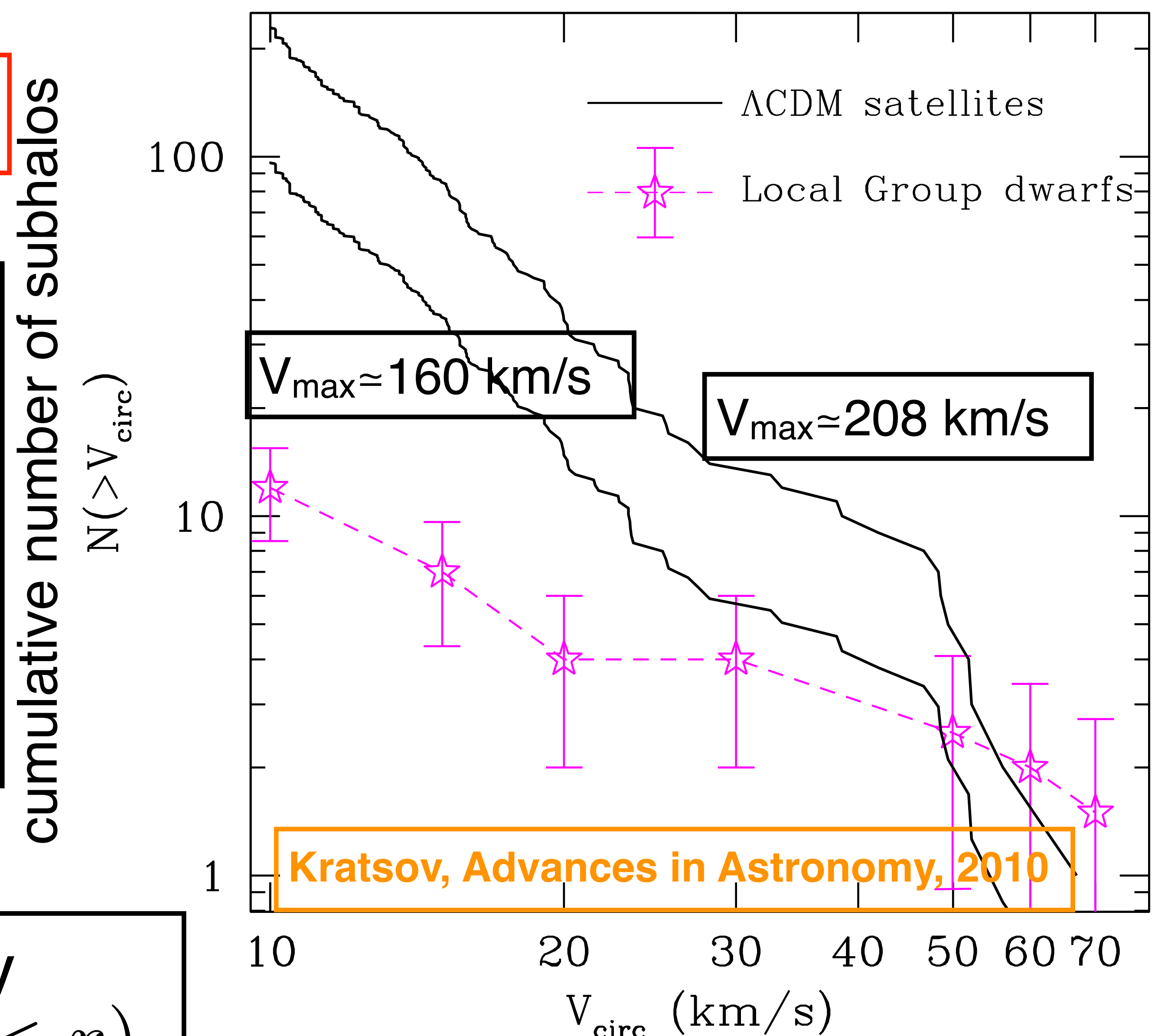
When *N*-body simulations in the ΛCDM model and observations are compared, problems appear at (sub-)galactic scales: **small scale crisis**

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

circular velocity

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



maximal circular velocity of subhalo

Small scale crisis II

cusp vs core problem

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

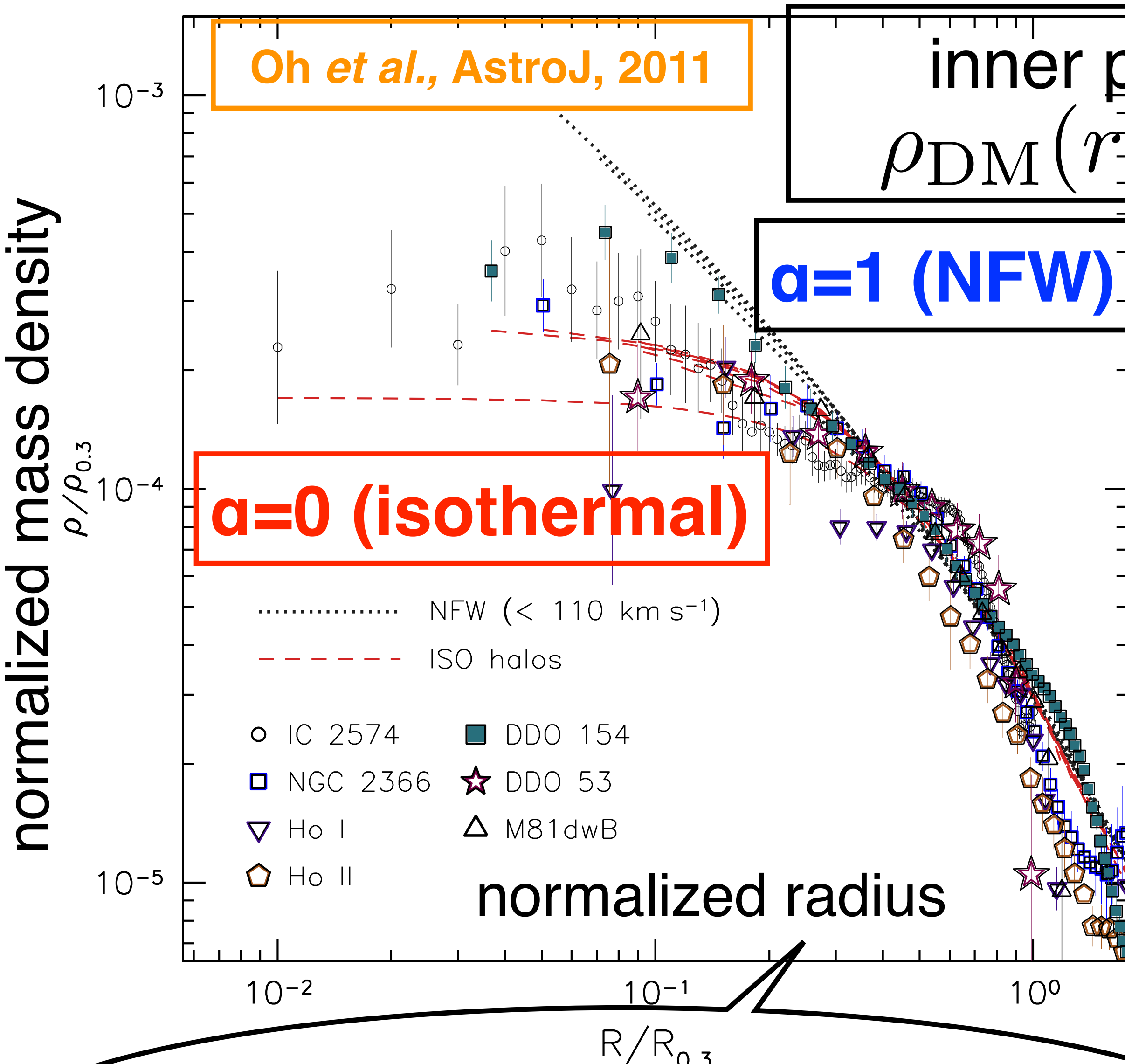
inner profile

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

α=1 (NFW)

α=0 (isothermal)

Oh *et al.*, AstroJ, 2011



field dwarf spheroidal galaxies
~10^9 Msun

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

NFW profile

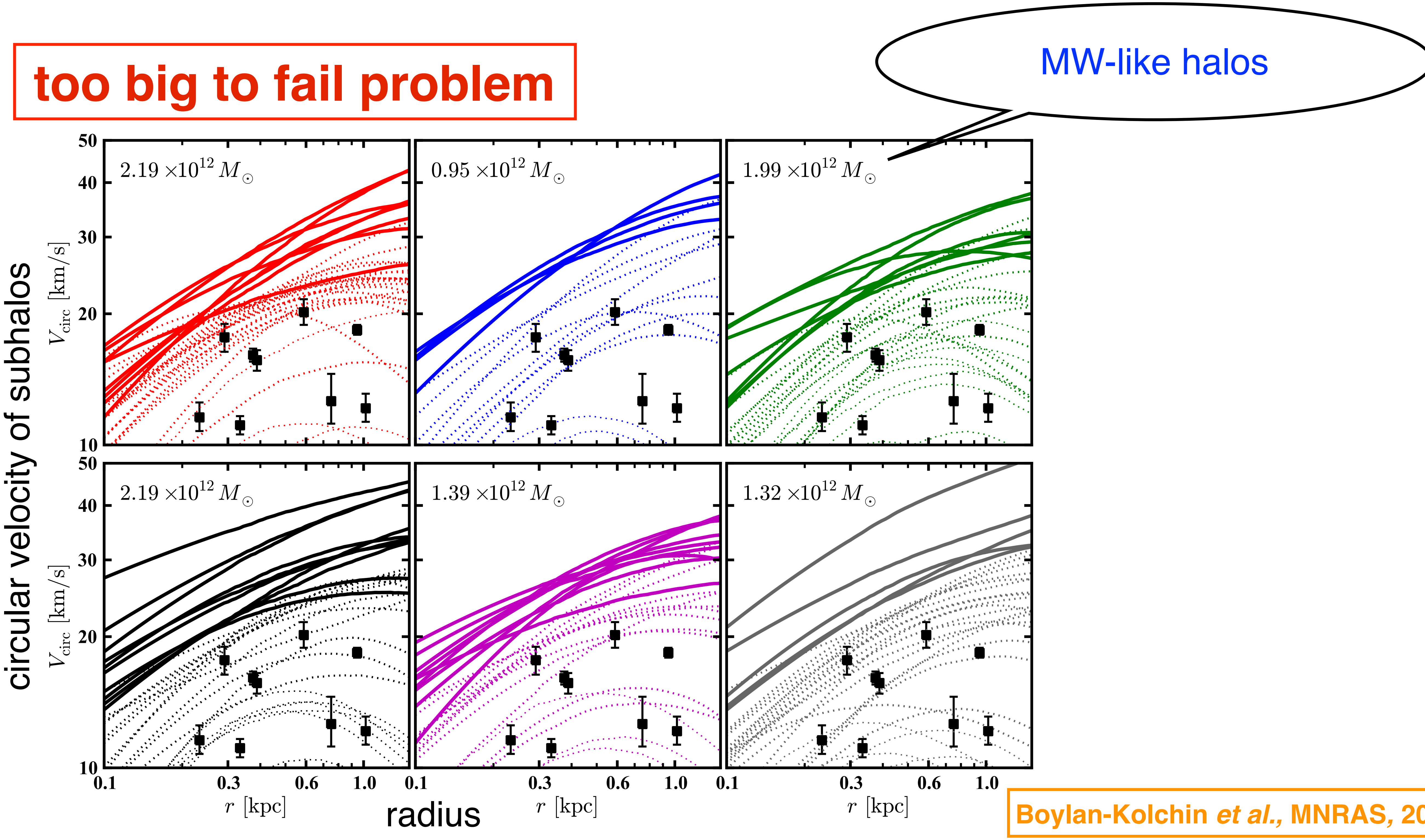
$$\rho_{\rm DM}(r) = \frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

isothermal profile

$$\rho_{\rm DM}(r) = \rho_{\rm DM}^0 \begin{cases} 1 & (r \ll r_0) \\ (r_0/r)^2 & (r \gg r_0) \end{cases}$$

Small scale crisis III

too big to fail problem



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

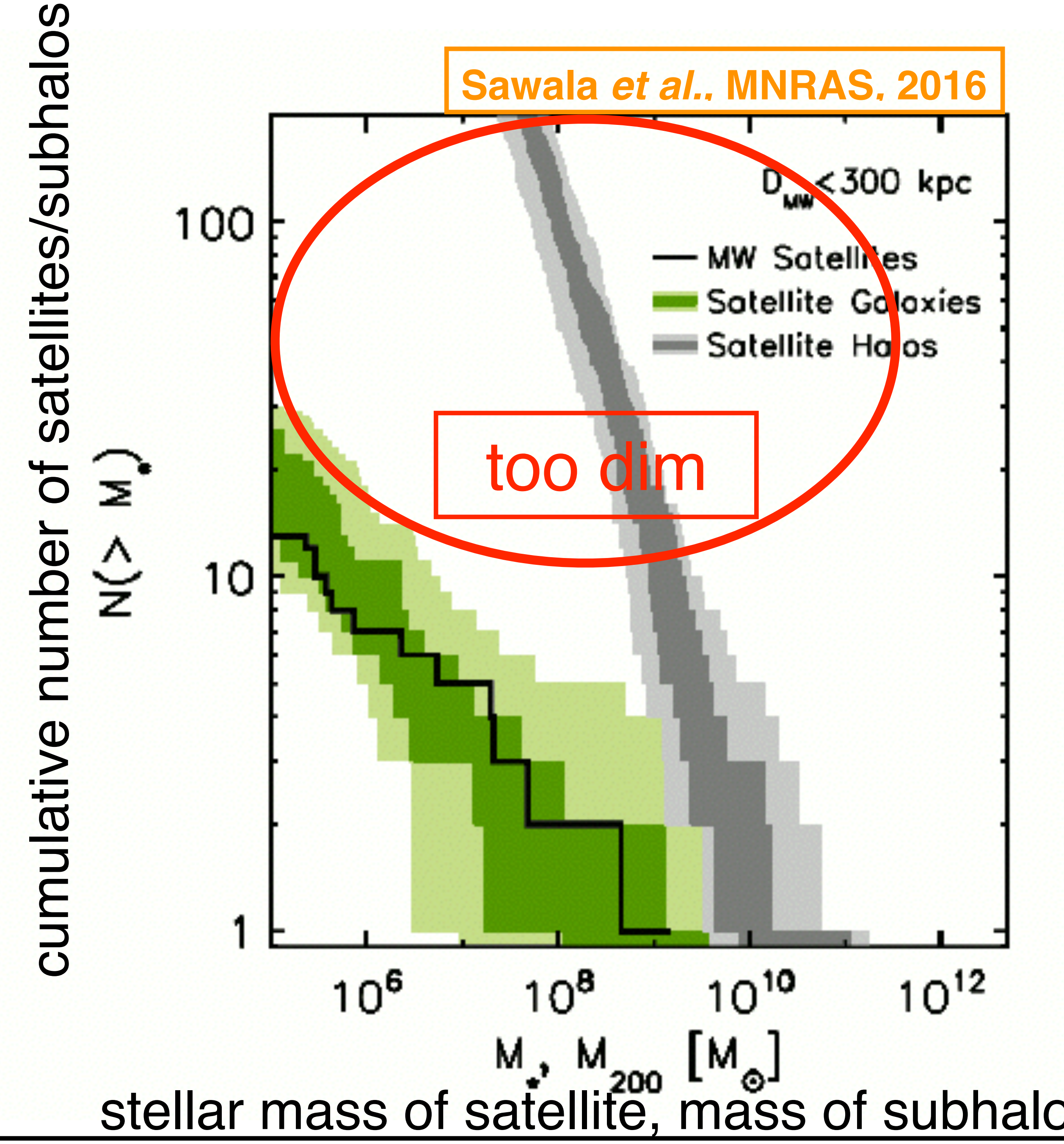
N-body (DM-only) simulations in ΛCDM model →
~10 subhalos with deepest potential wells in Milky Way-size halos do not have observed counterparts (dwarf spheroidal galaxies)

Possible solution I

Above Discussions are based on *N*-body (**DM-only**) simulations in the ΛCDM model

↕

Gravitational potentials are shallower at smaller scales → Baryonic heating and cooling processes may be important



Baryonic processes

- **heating from ionizing photons** - ionizing photons emitted and spread around reionization of the Universe heat and evaporate gases

- **mass loss by supernova explosions** - supernova explosions blow gases from inner region -> DM redistribute along shallower potential

Possible solution II

Above Discussions are based on
N-body (DM-only) simulations in the ΛCDM model

↕

alternative models ↔ nature of DM

- **Warmness** - thermal velocities induce pressure of DM fluid and prevent gravitational growth (Jeans analysis)

- **Interactions with relativistic particles** - DM fluid couples to relativistic particles in a direct/indirect manner

- **Self-interaction** - induced heat transfer of DM fluid heats DM particles in inner region and flatten inner profile

Physical meaning

Fokker-Planck equation - diffusion equation:

$$\frac{C[f_{\rm DM}]}{m_{\rm DM}} = \frac{\partial}{\partial \mathbf{p}_{{\rm DM}i}}\left[D\left(\frac{\partial f_{\rm DM}}{\partial \mathbf{p}_{{\rm DM}i}} + \frac{\mathbf{p}_{{\rm DM}i}/m_{\rm DM} - \mathbf{u}_i}{T} f_{\rm DM}\right)\right]$$

$$D = \frac{1}{6}\langle q^2 \sigma_{\rm el} v\rangle n_{\rm TP} = \frac{1}{6}\frac{(\Delta p)^2}{\Delta t}$$ - random walk in the momentum space

The collision term vanishes in equilibrium - detailed balance

$$f_{\rm DM} = f_{\rm DM}^{\rm eq} = \exp\left(-\frac{(\mathbf{p}_{\rm DM} - m_{\rm DM}\mathbf{u})^2}{2m_\chi T} - \frac{\mu_{\rm DM}}{T}\right) \Rightarrow C[f_{\rm DM}] = 0$$

The derived reaction rate reproduces that of Thomson scattering

$$\gamma = \frac{1}{6m_e T}\sum_{s_\gamma}\int \frac{d^3\mathbf{p}_\gamma}{(2\pi)^3} f_\gamma^{\rm eq}(1 \mp f_\gamma^{\rm eq}) \int_{-4\mathbf{p}_\gamma^2}^{0} dt(-t)\frac{d\sigma_T}{dt} v = \frac{4\bar\rho_\gamma}{3\bar\rho_b} a n_e \sigma_T$$

Important subtlety

Fokker-Planck approximation: expanding the collision term w.r.t. q/p

A systematic expansion of $C[f]$ w.r.t. q (mass dimension one!) is studied and found in the literature

DARK SUSY | Bringmann *et al.*, JCAP, 2007 | Bringmann *et al.*, New J. Phys, 2009

$$\tilde{\gamma} = \frac{1}{6 m_{\mathrm{DM}} T} \sum_{s_{\mathrm{TP}}} \int \frac{d^3 \mathbf{p}_{\mathrm{TP}}}{(2\pi)^3} f_{\mathrm{TP}}^{\mathrm{eq}} (1 \mp f_{\mathrm{TP}}^{\mathrm{eq}}) \int_{-4\mathbf{p}_{\mathrm{TP}}^2}^{0} dt(-t) \left.\frac{d\sigma}{dt} v\right|_{t \to 0}$$

forward scattering

Suppose a simplified model, where SM is extended with DM fermion (χ) and light Dirac fermions (ν) coupled to a mediator boson (ϕ)

A scalar mediator $\mathcal{L}_{\mathrm{S}} \supset g_\chi \bar{\chi}\phi\chi + g_\nu \bar{\nu}\phi\nu$ Bringmann *et al.*, PRL, 2012

$\bar{\nu}\nu \sim m_\nu + \mathcal{O}(q)$ ← the leading term is subdominant!!

CANNOT archive a late kinetic decoupling $T_{\mathrm{dec}} = \mathcal{O}(\mathrm{keV})$ from $\tilde{\gamma}$ in the literature

subgalactic damping

Scalar and vector operators

The argument in the literature seems a consequence of an inappropriate expansion of $C[f]$

We show the scalar operator **CAN** achieve a subgalactic damping as well as the vector operator $\mathcal{L}_{\rm V} \supset g_\chi \bar{\chi}\gamma^\mu \chi \phi_\mu + g_\nu \bar{\nu}\gamma^\mu \nu \phi_\mu$

$\bar{\nu}\gamma^\mu\nu \sim p_\nu^\mu \sim T \leftarrow$ not-suppressed by a small fermion mass

Estimate of the minimum halo mass from γ in our formalism

Vector:

$$(M_{\rm cut})_{\rm V} = 6.8\times 10^8\, M_\odot \left(\frac{r}{r_0}\right)^{9/2} \left(\frac{N_\nu}{6}\frac{\alpha_\nu}{10^{-4}}\frac{\alpha_\chi}{0.035}\right)^{3/4} \left(\frac{m_\chi}{1\,\rm TeV}\right)^{-3/4} \left(\frac{m_\phi}{1\,\rm MeV}\right)^{-3}$$

Scalar:

$$(M_{\rm cut})_{\rm S} = 6.6\times 10^8\, M_\odot \left(\frac{r}{r_0}\right)^{9/2} \left(\frac{N_\nu}{6}\frac{\alpha_\nu}{10^{-5}}\frac{\alpha_\chi}{0.17}\right)^{3/4} \left(\frac{m_\chi}{1\,\rm TeV}\right)^{-3/4} \left(\frac{m_\phi}{1\,\rm MeV}\right)^{-3}$$

Linear perturbation theory

Evolution equation in the Fourier space (synchronous gauge):

$$\dot{f}_1 + \frac{i\mathbf{k}_i\mathbf{q}_i}{am_\chi} f_1 - \gamma_0 a \underline{L_{\rm FP}}[f_1] = \dot{\eta}\frac{\mathbf{q}^2}{2a^2 m_\chi T_{\chi 0}} f_0 - \frac{\dot{h}+6\dot{\eta}}{2k^2}(\mathbf{k}_i\mathbf{q}_i)^2 \frac{1}{2a^2 m_\chi T_{\chi 0}} f_0 - \frac{i\mathbf{k}_i\mathbf{q}_i}{aT_{\chi 0}} \gamma_0 a \frac{\theta_{\rm TP}}{k^2} f_0$$
$$+ \left[\gamma_1 a \left(\frac{T_0}{T_{\chi 0}} - 1\right) + \gamma_0 a \frac{T_1}{T_{\chi 0}}\right]\left(\frac{\mathbf{q}^2}{2a^2 m_\chi T_{\chi 0}} - 3\right) f_0$$

Fokker-Planck operator:

$$L_{\rm FP}[f] = \frac{\partial}{\partial \mathbf{q}_i}\left[\mathbf{q}_i f + a^2 m_\chi T_0 \frac{\partial}{\partial \mathbf{q}_i} f\right]$$

Expansion with the eigenfunctions:

$$f_1(\mathbf{k},\mathbf{q},\tau) = \frac{1}{(2\pi a^2 m_\chi T_0)^{3/2}} e^{-y} \sum_{n,\ell=0}^{\infty} (-i)^\ell (2\ell+1) S_{n\,\ell}(y) P_\ell(\hat{\mathbf{k}}_i\hat{\mathbf{q}}_i) f_{n\ell}(k,\tau)$$

$$S_{n\,\ell}(y) = y^{\ell/2} L_n^{\ell+1/2}(y)$$

$$\phi_{n\,\ell\,m} = e^{-y} S_{n\ell}(y) Y_{\ell\,m}(\hat{\mathbf{q}})$$

$$L_{\rm FP}\phi_{n\,\ell\,m} = -(2n+\ell)\phi_{n\,\ell\,m}$$

Boltzmann hierarchy

Boltzmann hierarchy of $f_{n\ell}(k,\tau)$ (synchronous gauge):

$$\begin{aligned}
&\dot{f}_{n\ell} + (2n+\ell)(\gamma_0 a + R) f_{n\ell} - 2nR f_{n-1\ell} \\
&\quad + k\sqrt{\frac{2T_0}{m_\chi}}\left\{\frac{\ell+1}{2\ell+1}\left[\left(n+\ell+\frac{3}{2}\right) f_{n\ell+1} - n f_{n-1\ell+1}\right] + \frac{\ell}{2\ell+1}(f_{n+1\ell-1} - f_{n\ell-1})\right\} \\
&= \delta_{\ell 0}\left\{-\frac{1}{2}A_n \dot{h} + \frac{1}{3}B_n \dot{h} - 2B_n\left[\gamma_1 a\left(\frac{T_0}{T_{\chi 0}} - 1\right) + \gamma_0 a \frac{T_1}{T_{\chi 0}}\right]\right\} \\
&\quad + \delta_{\ell 1}\frac{1}{3}A_n k\sqrt{\frac{2m_\chi}{T_0}}\gamma_0 a \frac{\theta_{\rm TP}}{k^2} + \delta_{\ell 2}\frac{2}{15}\frac{T_{\chi 0}}{T_0}A_n(\dot{h} + 6\dot{\eta})
\end{aligned}$$

with

$$R = \frac{d\ln(aT_0^{1/2})}{d\tau}\,, \quad A_n = \left(1 - \frac{T_{\chi 0}}{T_0}\right)^n, \quad B_n = n\frac{T_{\chi 0}}{T_0}\left(1 - \frac{T_{\chi 0}}{T_0}\right)^{n-1}$$

$\gamma/H > 1$ (coupled) → $A_0 = 1$, $B_1 = 1$, the others vanish

$\gamma/H < 1$ (decoupled) → $A_n = 1$, the others are tiny

Only low multipole $\ell = 0, 1, 2$ (& $n = 0, 1$ when $\gamma/H > 1$) components couple to the gravity

DM imperfect fluid

Low multipole components are related with the primitive variables of DM imperfect fluid: mass density ρ, bulk velocity potential θ, pressure P, anisotropic inertia σ

DM sound speed:
$$c_\chi^2 = \frac{T_{\chi 0}}{m_\chi}\left(1 - \frac{1}{3}\frac{d\ln T_{\chi 0}}{d\ln a}\right)$$

$$\delta = f_{00}\,,\ \theta = 3k\sqrt{\frac{T_0}{2m_\chi}}f_{01}\,,\ \delta P = \frac{T_0}{T_{\chi 0}}\bar{P}(f_{00} - f_{10}) = \bar{\rho}(c_\chi^2\delta + \pi)\ ,\ \ \sigma = 5\frac{T_0}{m_\chi}f_{02}$$

$$\bar{\rho}(1+\delta) = -T^0{}_0 = a^{-4}\sum_{s_\chi}\int\frac{d^3\mathbf{q}}{(2\pi)^3}\,m_\chi\,f$$

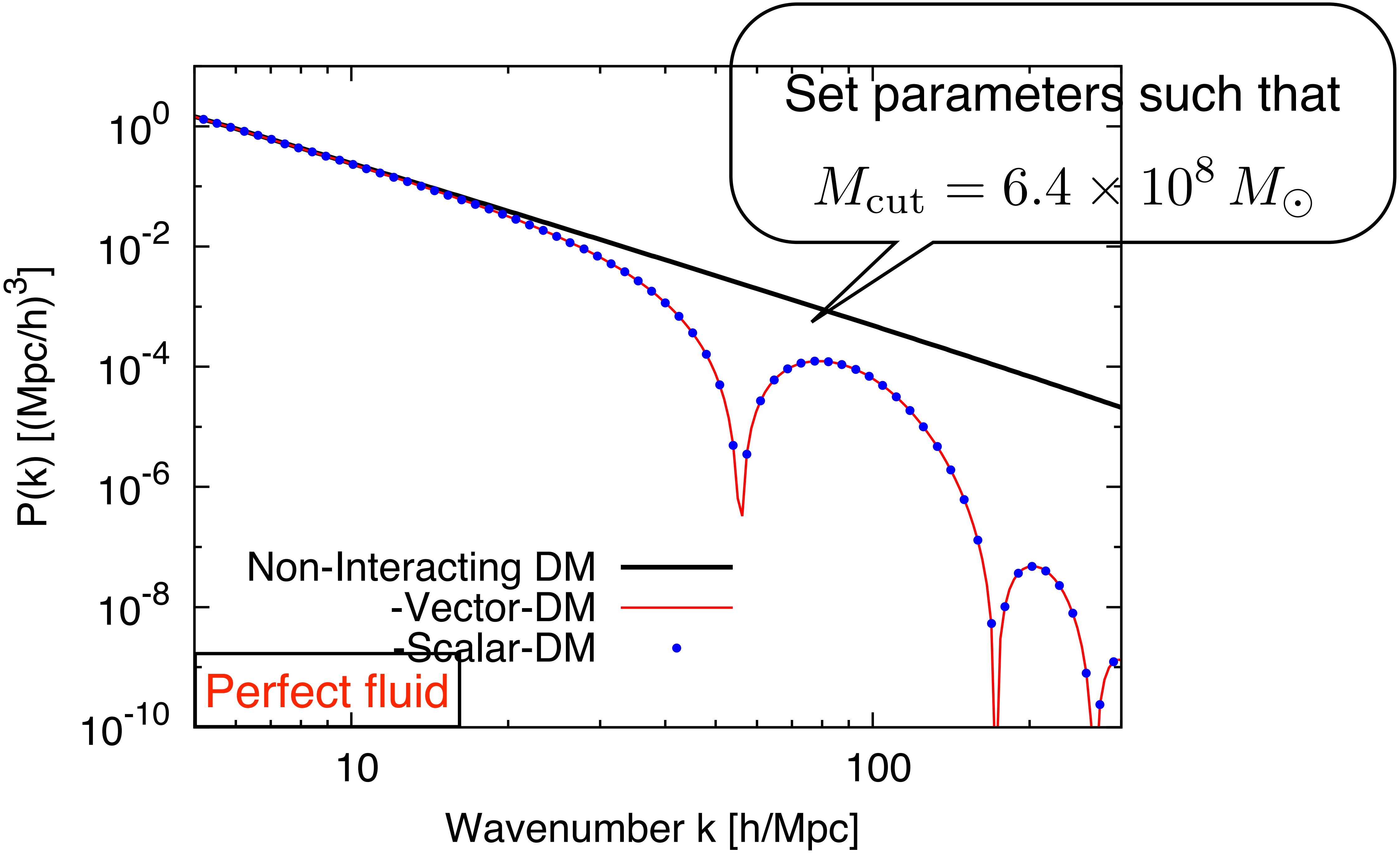
$$(\bar{\rho}+\bar{P})\theta = i\mathbf{k}_i T^i{}_0 = a^{-4}\sum_{s_\chi}\int\frac{d^3\mathbf{q}}{(2\pi)^3}\,i\mathbf{k}_i\mathbf{q}_i\,f$$

$$\bar{P} + \delta P = \frac{1}{3}T^i{}_i = a^{-4}\sum_{s_\chi}\int\frac{d^3\mathbf{q}}{(2\pi)^3}\,\frac{\mathbf{q}^2}{3m_\chi}\,f$$

$$(\bar{\rho}+\bar{P})\sigma = -\left(\hat{\mathbf{k}}_i\hat{\mathbf{k}}_j - \frac{1}{3}\delta_{ij}\right)T^i{}_j = -a^{-4}\sum_{s_\chi}\int\frac{d^3\mathbf{q}}{(2\pi)^3}\,\frac{\mathbf{q}^2}{m_\chi}\left[(\hat{\mathbf{k}}_i\hat{\mathbf{q}}_i)^2 - \frac{1}{3}\right]\,f$$

Linear matter power spectra

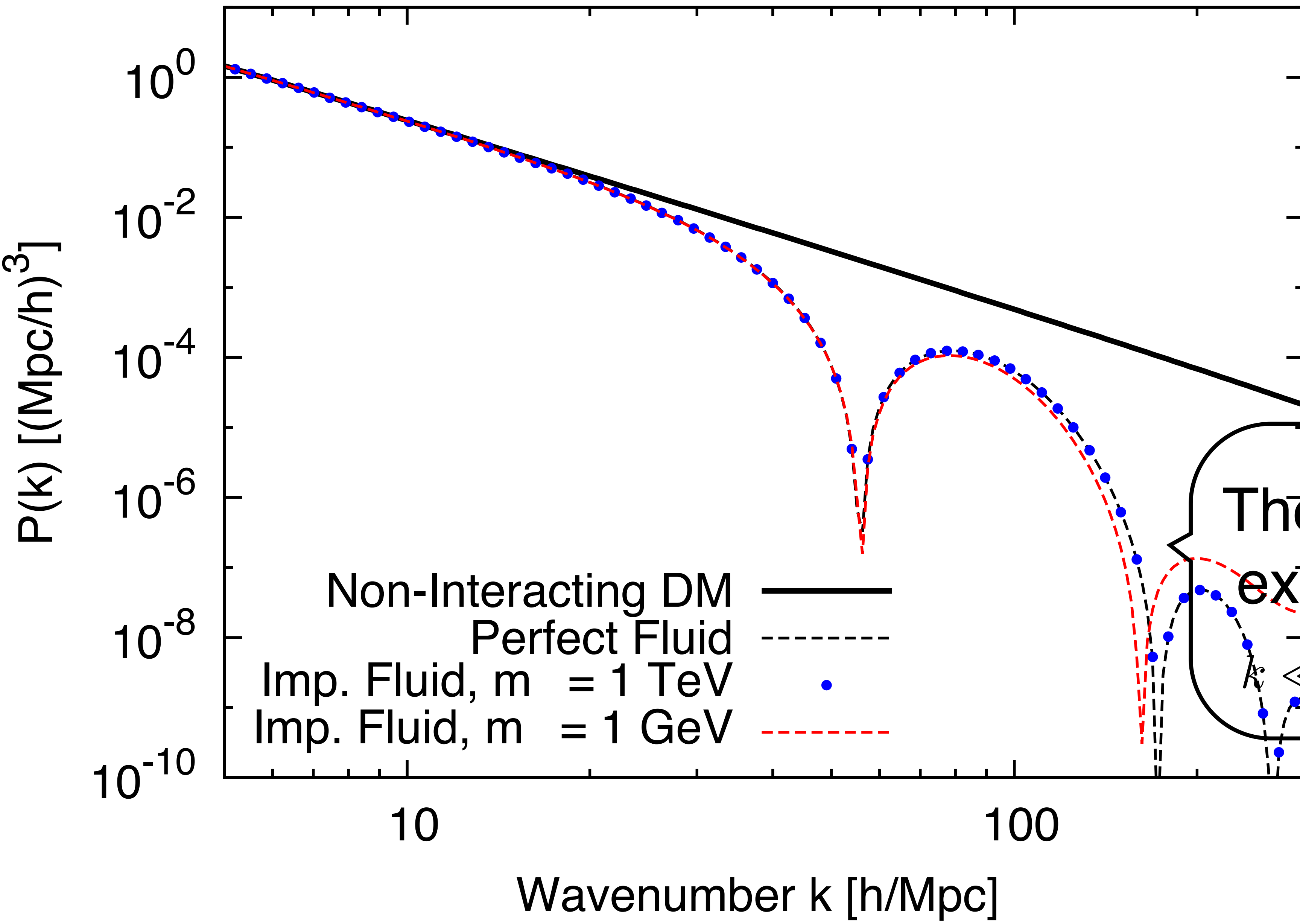
Scalar vs Vector operators



The scalar operator **CAN** achieve a subgalactic damping as well as the vector operator

Validity of perfect fluid description

Perfect vs imperfect fluid approximations



The effects of
the higher order terms
are suppressed by

$$\frac{k}{aH}\sqrt{\frac{T_0}{m_\chi}}$$

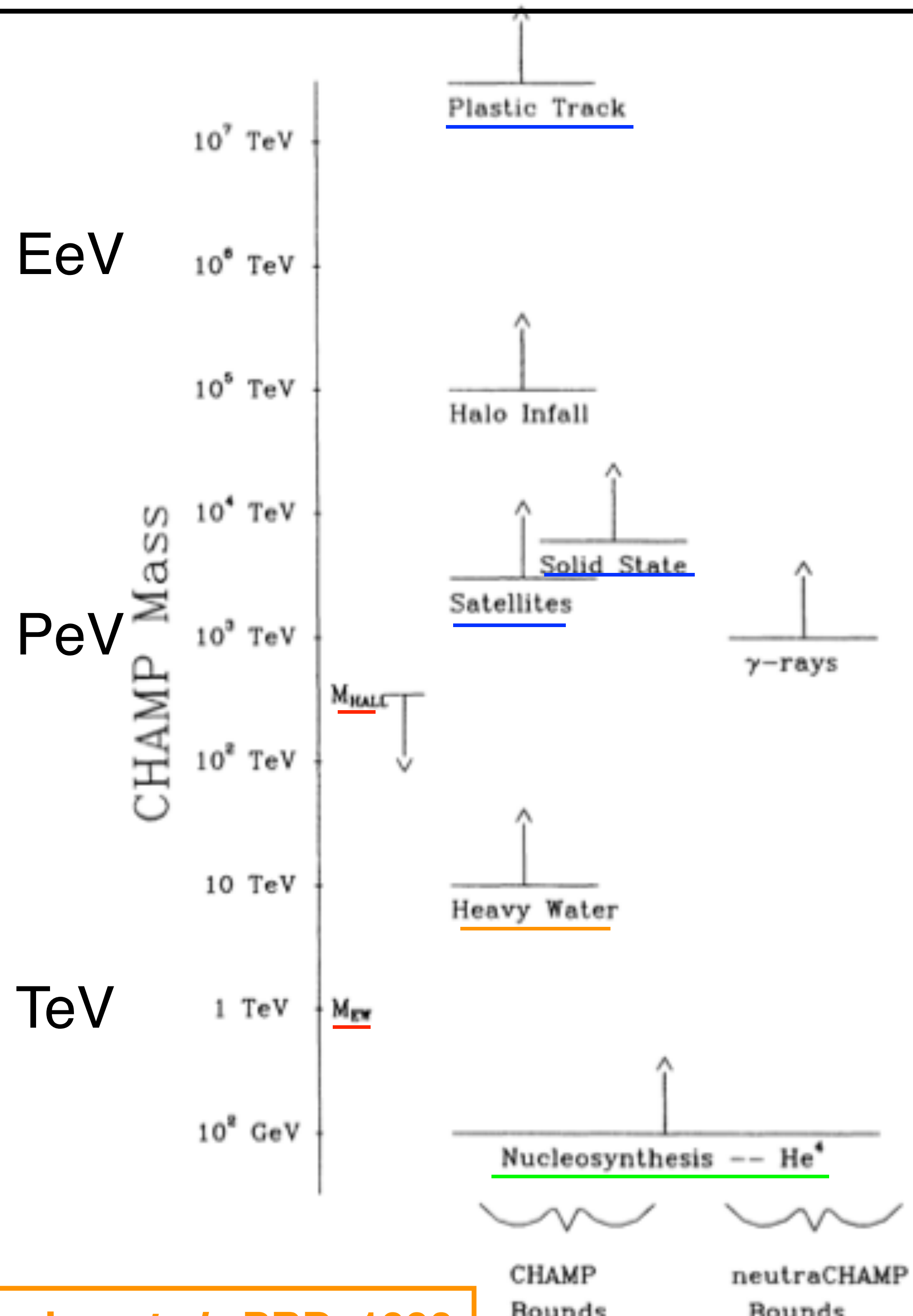
The perfect fluid description is
expected to be trustworthy at

$$k \ll 430\,/\mathrm{Mpc} \times \left(\frac{r}{r_0}\right)^{-1/2} \left(\frac{m_\chi}{\mathrm{GeV}}\right)^{1/2}$$

Mismatching of the two approximations DOES NOT NECESSARILY
means that the imperfect fluid description is better,
but it means that we need to follow the full Boltzmann hierarchy

Application to electrically charged DM

CHAMP (CHArged Massive Particle):
DM particle carries the electromagnetic charge
positive charge ($Y_{\rm Ch} \ll Y_{^4{\rm He}}$): X^+, $(X^{-\,4}{\rm He})$ Kohri *et al.*, PLB, 2010



Dimopoulos *et al.*, PRD, 1990

quasi-stable: $\tau_{\rm Ch} > 10^{10}$ yr
(age of the Universe)

_: thermal relic
_: Pioneer 11
_: improved to $m_{\rm Ch} > 10^8$ GeV
Verkerk *et al.*, PRL, 1992
_: more stringent $m_{\rm Ch} > 10^6$ GeV
from Catalyzed BBN
$(X^{-\,4}{\rm He}) + {\rm D} \rightarrow {}^6{\rm Li} + X^-$

Above the Planck scale!!

direct detection:
$m_{\rm Ch} > 10^{22}$ GeV (LUX)

Caveats

The severer terrestrial constraints are NOT applicable IF

Chuzoy *et al.*, JCAP, 2009

the Galactic magnetic field expels CHAMPs
from the the Galactic disk (Fermi acceleration)
& prevents CHAMPs from crossing the Galactic disk
(a small gyroradius) ➡ 10^5 GeV < m_{Ch} < 10^{11} GeV

CHAMP decays to a neutral particle (DM at present) at some point

➡ **Impacts on CMB** if $\tau_{Ch} > 10^5$ yr (recombination) ?

Analytic estimate from A. De Rujula, S. L. Glashow (!), and U. Sarid, Nucl. Phys. B, 1990

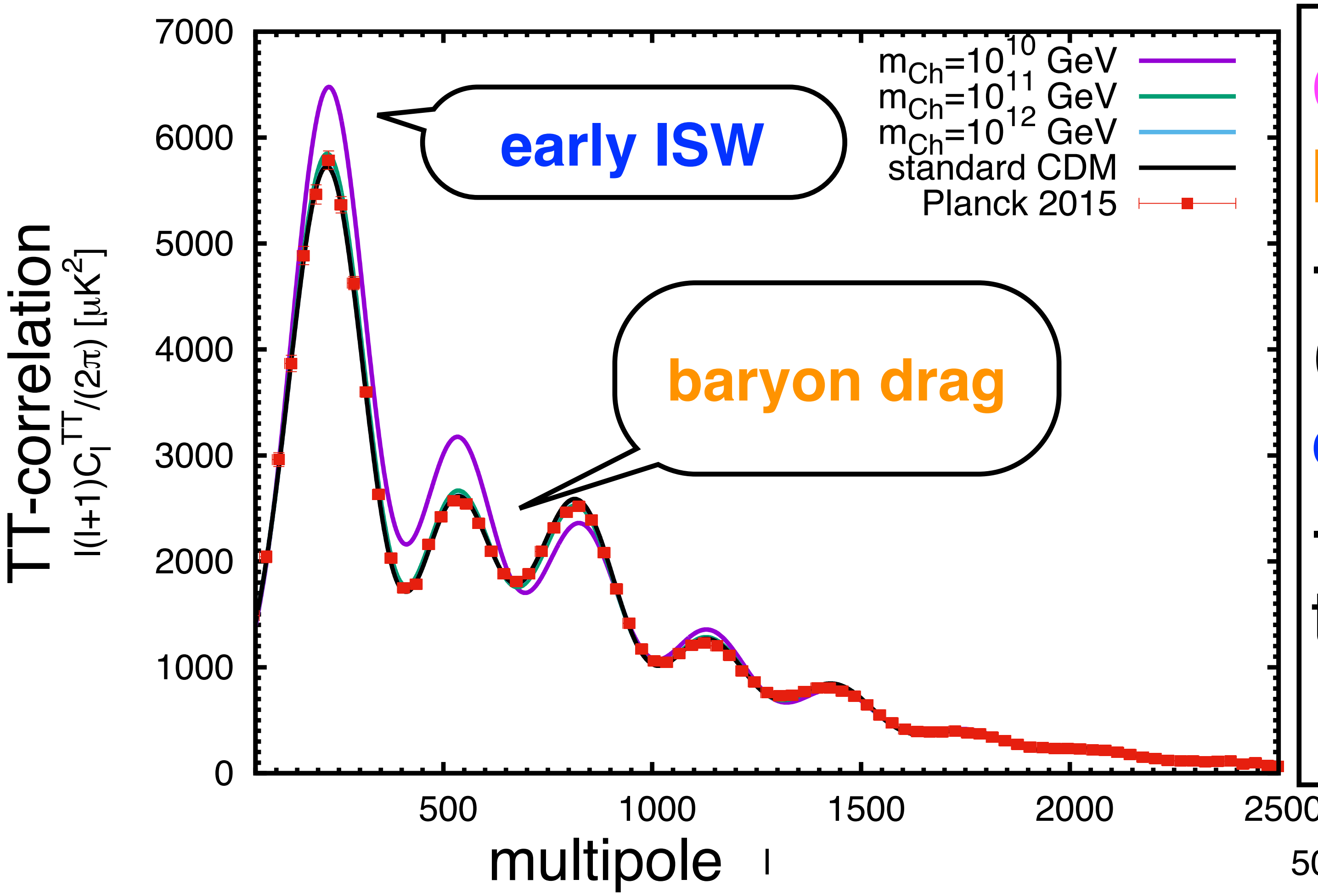
appropriate dynamical time scale. Survival of champ–baryon fluctuations requires that $t_1 > t_R$ at T_R, which, according to (4.2) obliges $M > 10^5$ PeV. This result is far

True in elaborate and modern analysis ?

t-averaging is important $\left.\frac{d\sigma}{dt}\right|_{t\to 0} \to \infty$

AK, K. Kohri, T. Takahashi, N. Yoshida, arXiv:1604.07926

Effects on CMB temperature and polarization spectra



CHAMP effects:

baryon drag

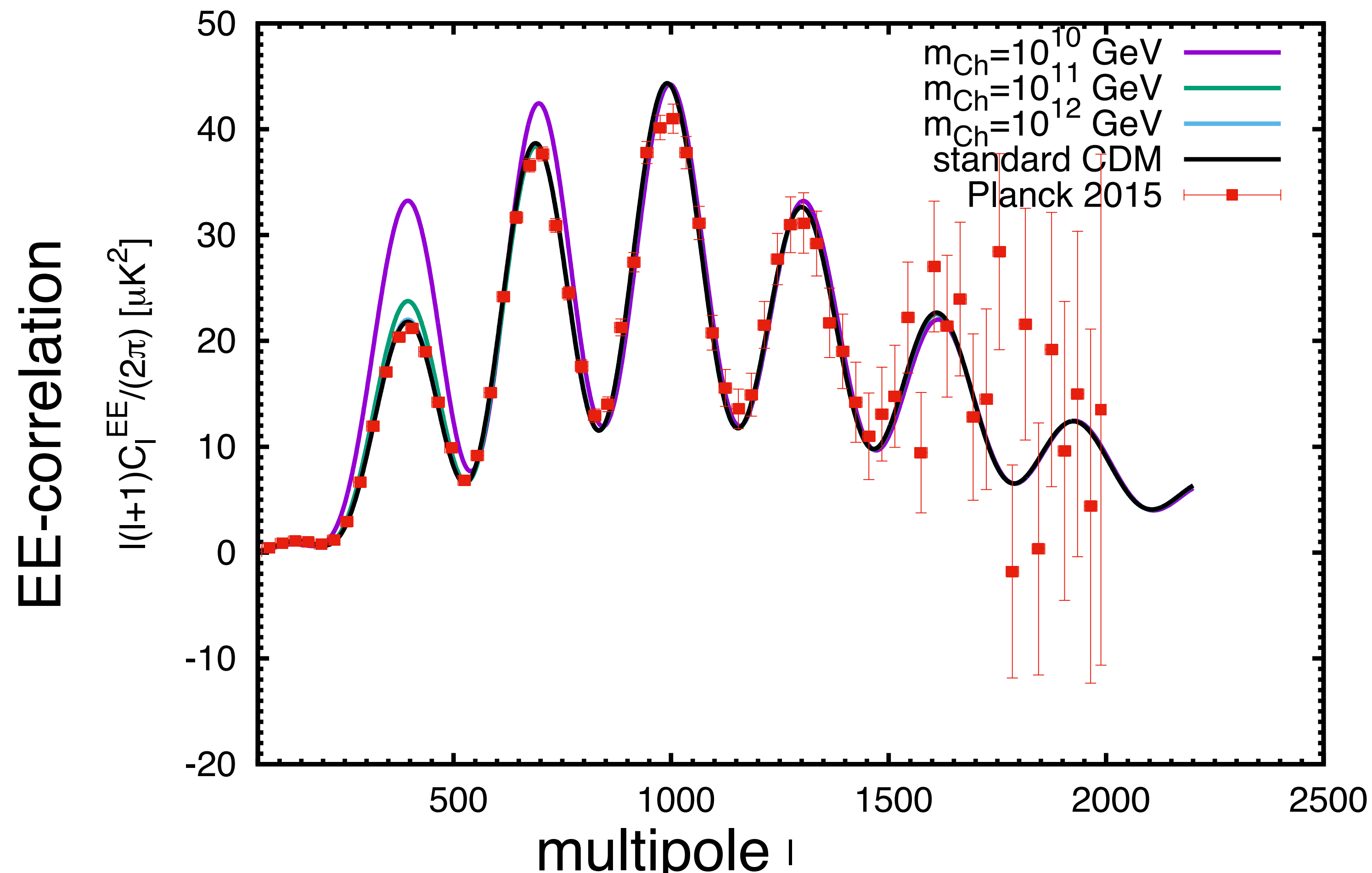
- CHAMPs and baryons compress (heat) the primordial plasma

early Integrated Sachs-Wolfe (ISW)

- CHAMPs cannot sustain the gravitational potential

→ photons obtains a net energy

The EE-correlation is MORE sensitive to the re-coupling of CHAMP when compared to the TT-correlation



$m_{Ch} > 10^{11}$ GeV (modern) coincides with the analytic estimate of DGS (1990)!