Interacting Dark Matter and Radiation in Cosmology

Yong TANG(湯勇)

University of Tokyo

Physics in LHC and the Early Universe, Jan 9-11, 2017

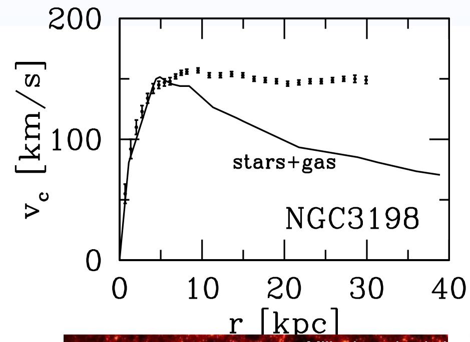
*based on P.Ko&**YT**,***1608.01083***(PLB)*,**1609.02307**;
YT,**1603.00165***(PLB)*

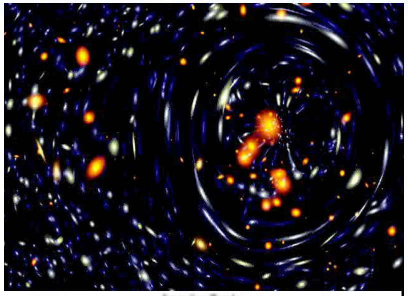
Outline

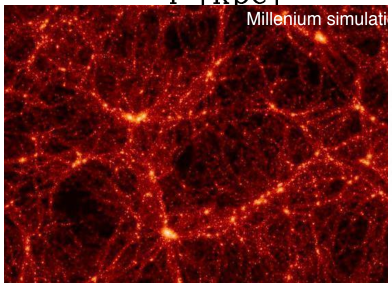
- Introduction & Motivation
  - Dark Matter evidence
  - Hubble constant and structure growth
- Interacting Dark Matter&Dark Radiation
  - U(1) dark photon
  - Residual Yang-Mills Dark Matter
- Summary

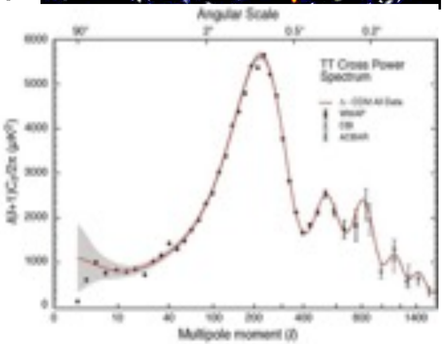
Dark Matter Evidence

- Rotation Curves of Galaxies
- Gravitational Lensing
- Large Scale Structure
- CMB anisotropies, …



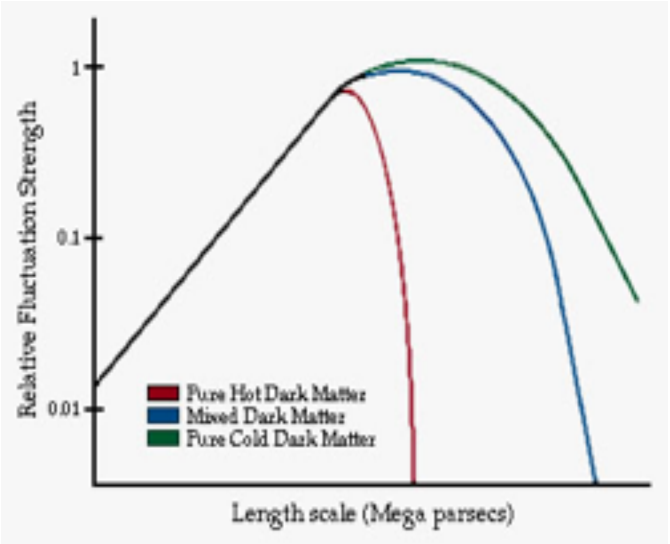






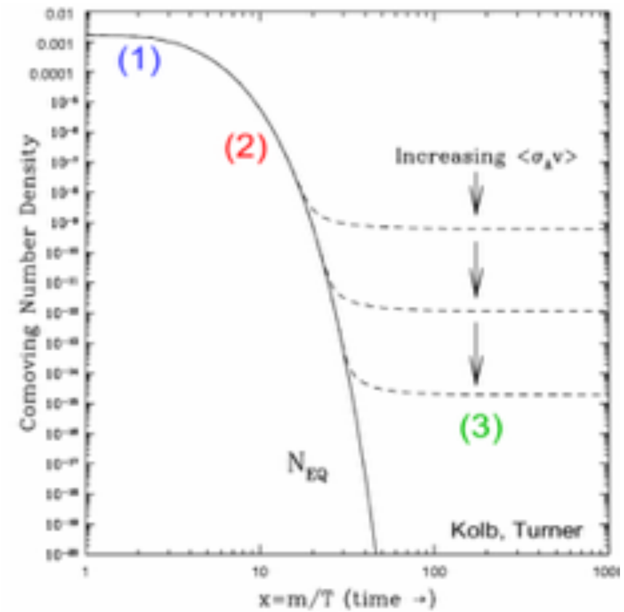
All confirmed evidence comes from gravitational interaction

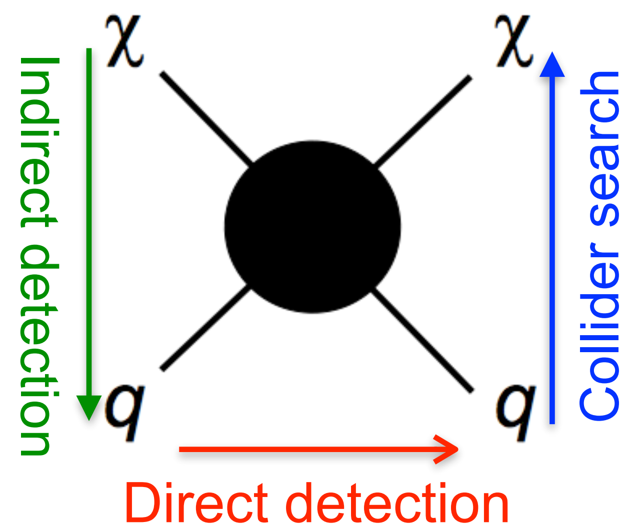
CDM: negligible velocity, WIMP
WDM: keV sterile neutrino
HDM: active neutrino



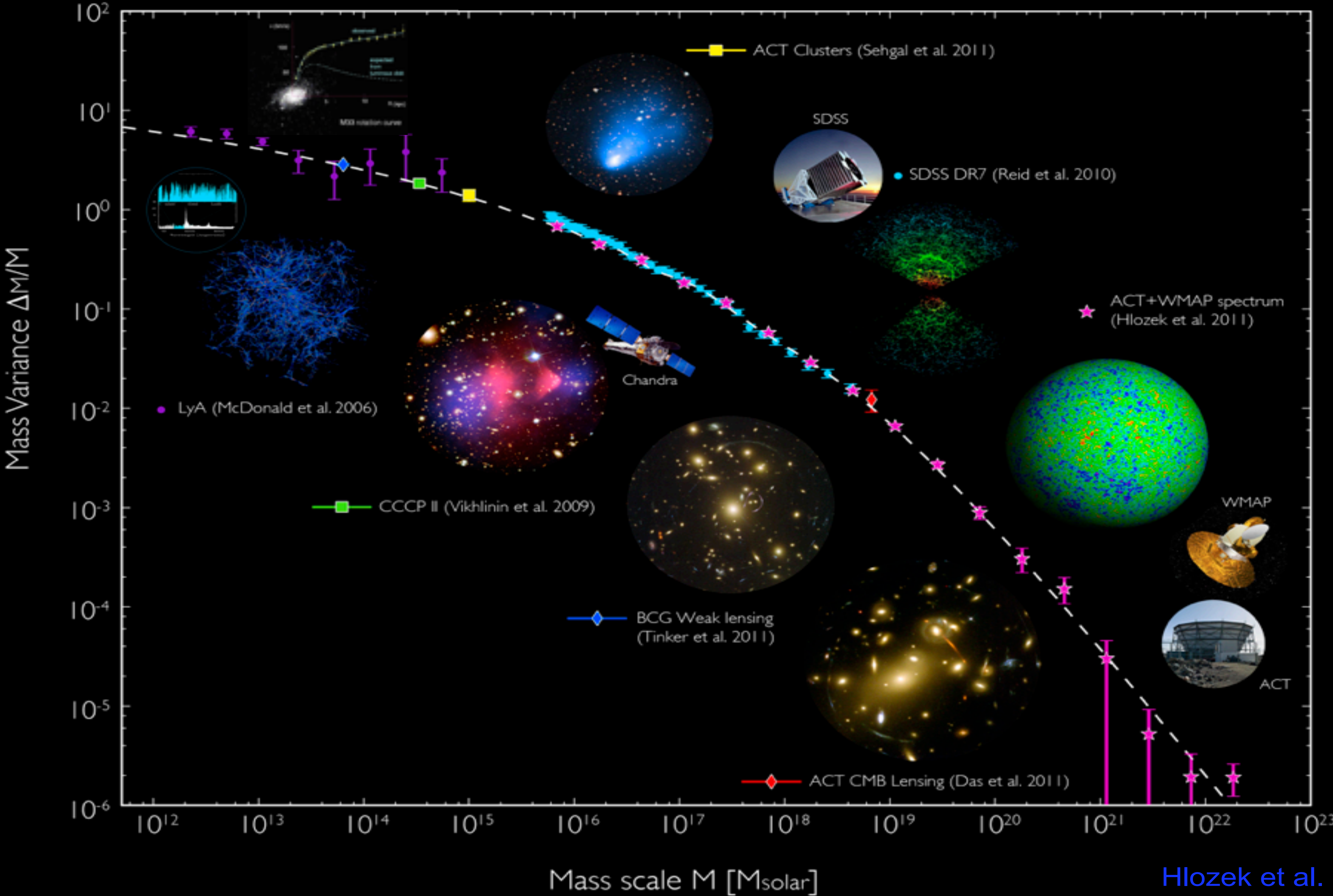
Weakly Interacting Massive Particle

- Mass around ~100GeV
- Coupling ~ 0.5
- abundance Ω~0.3
- Thermal History
  - Equilibrium XX<>ff
  - Equilibrium XX >ff
  - Freeze-out
- Cold Dark Matter (CDM)





ΛCDM: successful on large scales



Hlozek et al. 2012

Theoretical Scenarios

Supersymmetry

Extra-dimension

Sterile Neutrino

Axion

Wimpzilla

Dark atom/pion/glueball

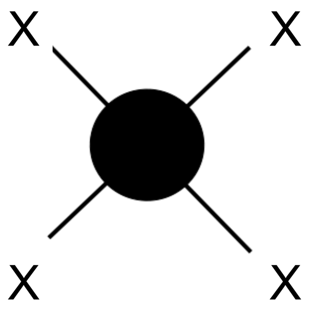
Bose-Einstein condensate

Primordial black hole

…

Why Interacting DM

- Theoretically motivated
  - Atomic DM, Mirror DM, Composite DM,…
  - Eventually, all DM is *interacting* in some way, the question is how strongly?
  - Self-Interacting DM $\frac{\sigma}{M_X} \sim \mathrm{cm}^2/\mathrm{g} \sim \mathrm{barn}/\mathrm{GeV}$ Spergel,Sigurdson,Boehm,Kaplinghat Loeb,Feng,Tulin,Yu,Bringmann,…
- Possible new testable signatures
  - *CMB, LSS, BBN*
  - Other astrophysical effects,…



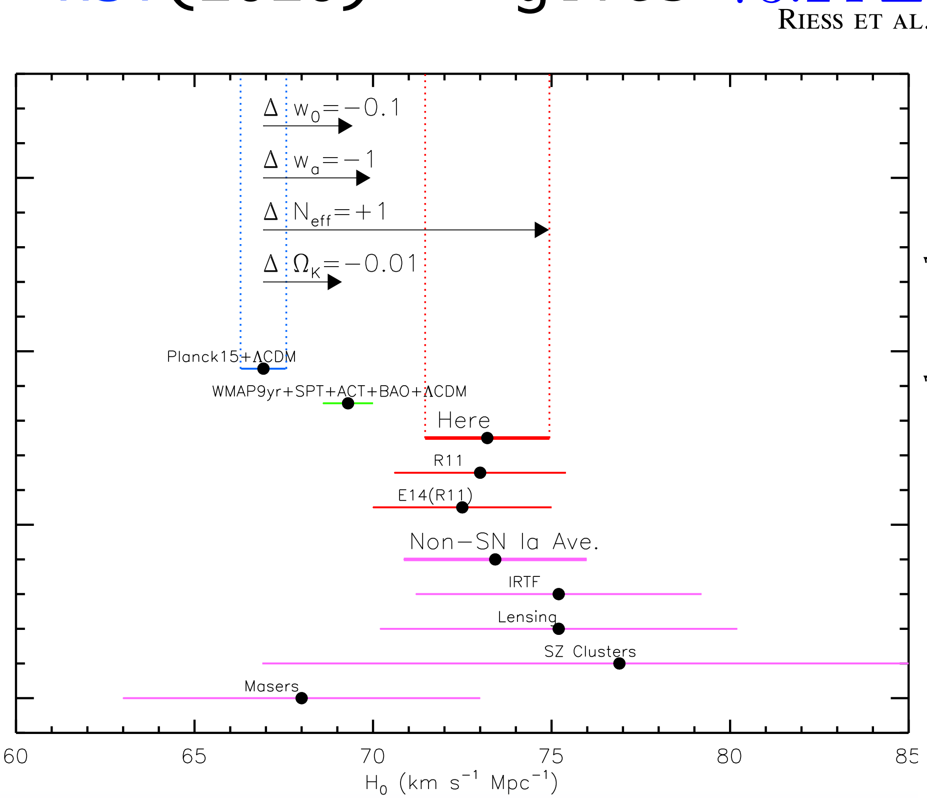
- Solution of CDM controversies
  - *Cusp-vs-Core, Too-big-to-fail, missing satellite,…*
  - H_0, σ_8? 2-3σ, systematic uncertainty

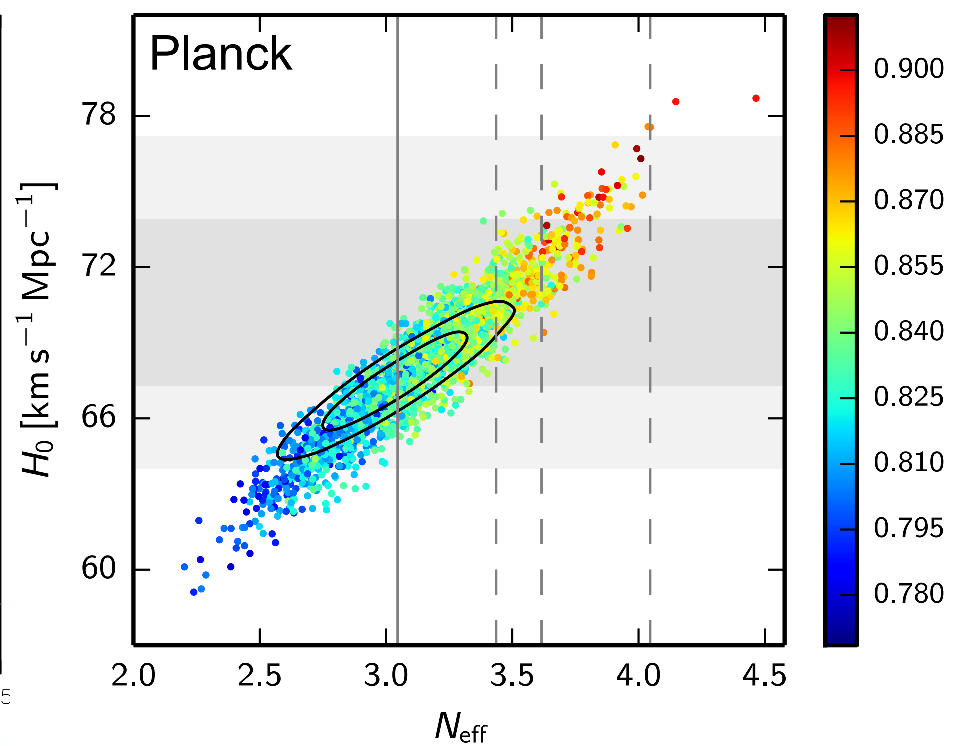
Tension in Hubble Constant?

- Hubble Constant H_0 defined as the present value of

$$H \equiv \frac{1}{a}\frac{da}{dt} = \frac{\sqrt{\rho_r + \rho_m + \rho_\Lambda}}{M_p}$$

- Planck(2015) gives $67.8 \pm 0.9\ \mathrm{km\ s^{-1} Mpc^{-1}}$
- HST(2016) gives $73.24 \pm 1.74\ \mathrm{km\ s^{-1} Mpc^{-1}}$





Tension in σ8 ?

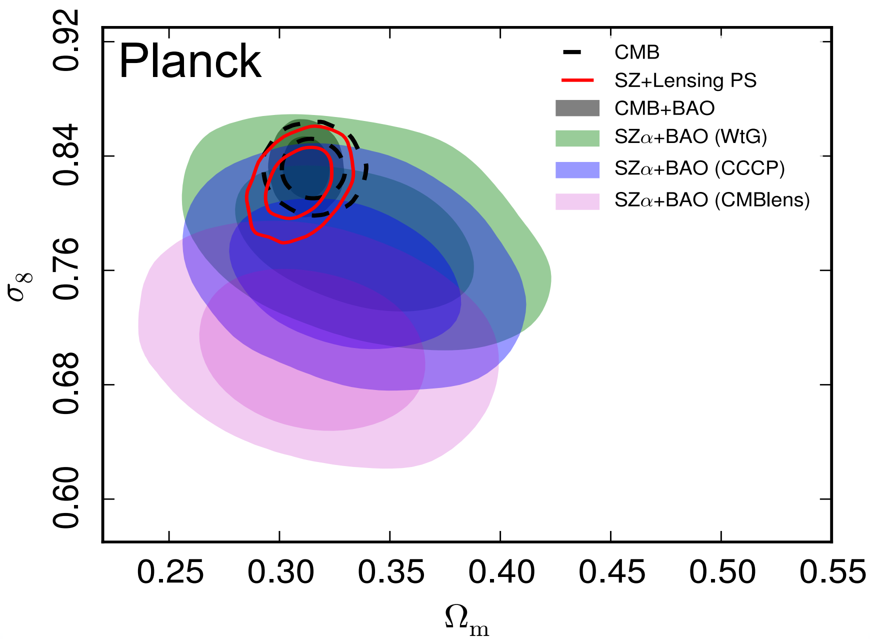
- Variance of perturbation field → collapsed objects

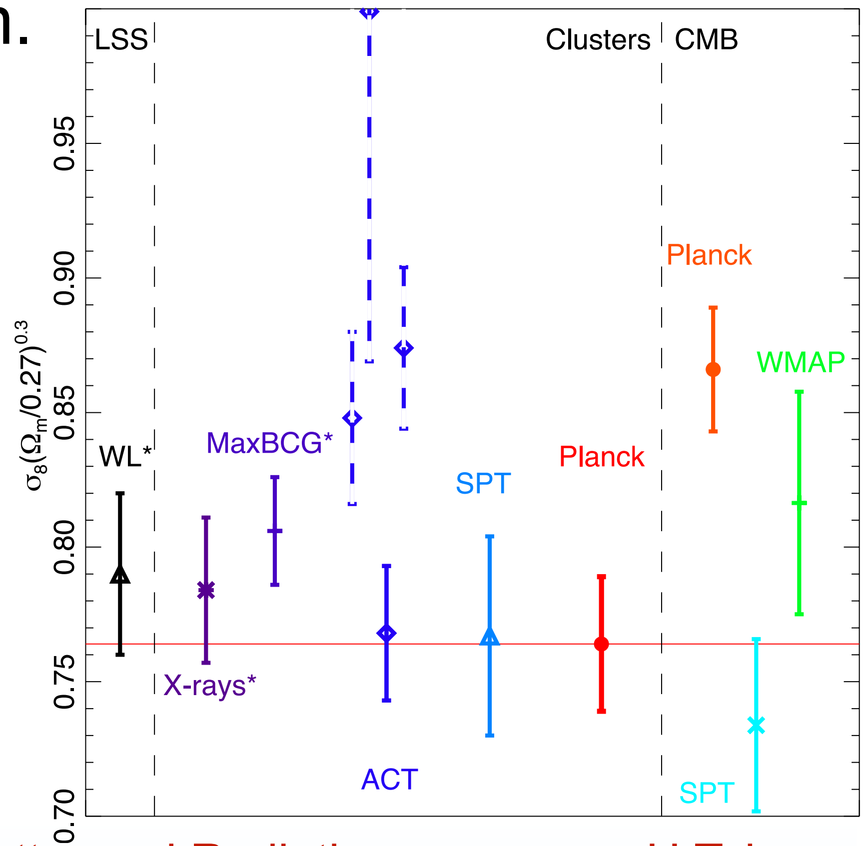
$$\sigma^2(R) = \frac{1}{2\pi^2}\int W_R^2(k) P(k) k^2 dk,$$

- where the filter function $W_R(k) = \frac{3}{(kR)^3}\left[\sin(kR) - kR\cos(kR)\right],$

  $P(k)$ is matter power spectrum.

- $\sigma_8 \equiv \sigma(8h^{-1}\mathrm{Mpc})$





Tension in σ_8 ?

Planck2015, Sunyaev–Zeldovich cluster counts

Data	$\sigma_8\left(\frac{\Omega_m}{0.31}\right)^{0.3}$	Ω_m	σ_8
WtG + BAO + BBN	0.806 ± 0.032	0.34 ± 0.03	0.78 ± 0.03
CCCP + BAO + BBN **[Baseline]**	0.774 ± 0.034	0.33 ± 0.03	0.76 ± 0.03
CMBlens + BAO + BBN	0.723 ± 0.038	0.32 ± 0.03	0.71 ± 0.03
CCCP + H_0 + BBN	0.772 ± 0.034	0.31 ± 0.04	0.78 ± 0.04

Planck2015, Primary CMB

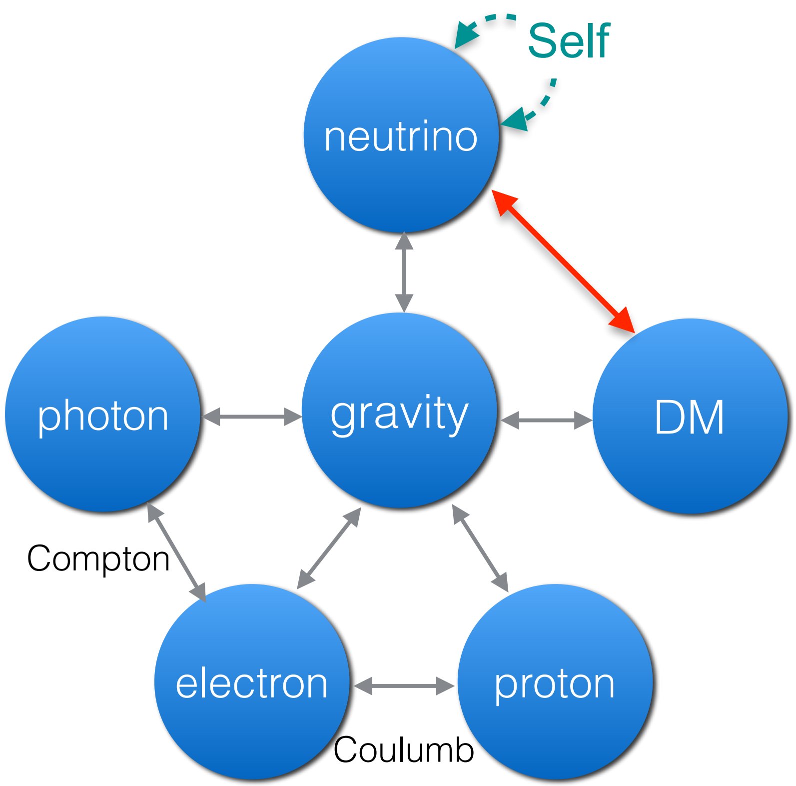
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012

Interacting Dark Matter and Radiation

- all components are connected by Einstein's equation

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

- first-order perturbation of Boltzmann equation
  - anisotropy in CMB
  - matter power spectrum for LSS
- (Self-)Interaction sometimes also matters



Interacting Radiation

- free-streaming

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu + 4\dot{\phi} ,$$

$$\dot{\theta}_\nu = k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) + k^2\psi ,$$

$$\dot{F}_{\nu l} = \frac{k}{2l+1}\left[lF_{\nu(l-1)} - (l+1)F_{\nu(l+1)}\right] ,$$

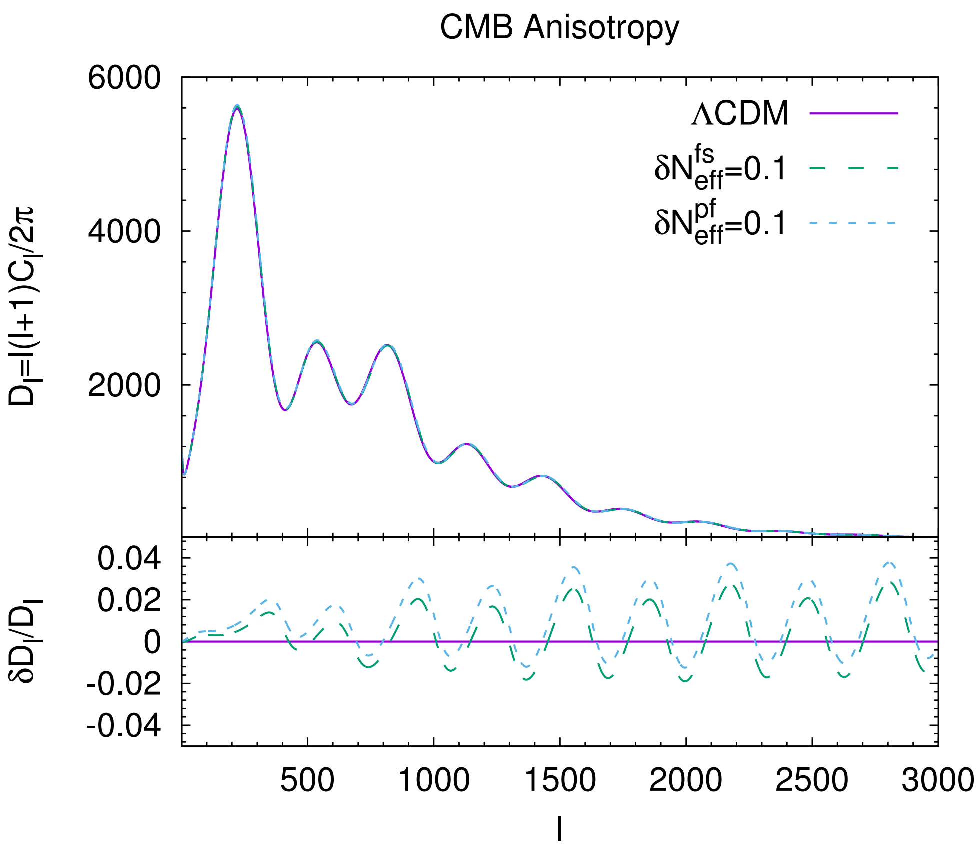
- perfect fluid $\Gamma \gg \mathcal{H}$

$$\dot{\delta}_\nu = -\frac{4}{3}\theta_\nu + 4\dot{\phi} ,$$

$$\dot{\theta}_\nu = k^2\left(\frac{1}{4}\delta_\nu - \sigma_\nu\right) + k^2\psi ,$$

$\sigma_\nu=0$

Y.Tang, arXiv:1603.00165(PLB)



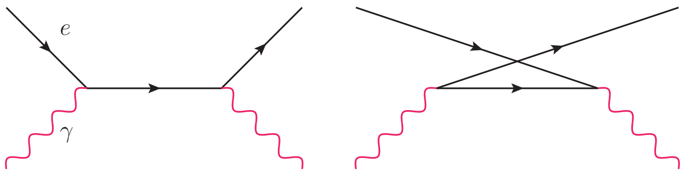
Neutrinos as perfect fluid excluded,
***Audren* et al 1412.5948**

Relation to Particle Physics

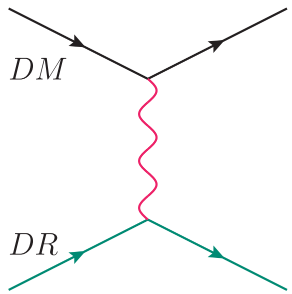
- The precise form of the scattering term, <σc>, is fully determined by the underlying microscopic or particle physics model, for example

IR behaviour

  - electron-photon, $\langle\sigma c\rangle \sim 1/m^2$
    Thomson scattering



  - DM-radiation with massive mediator, $\langle\sigma c\rangle \sim T^2/m^4$
    Boehm *et al*(astro-ph/0410591,1309.7588)

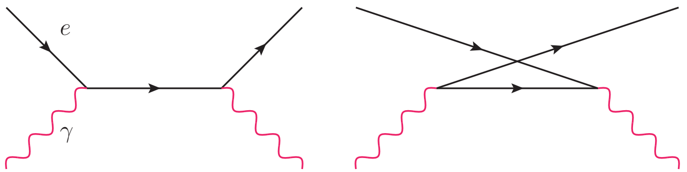


Relation to Particle Physics

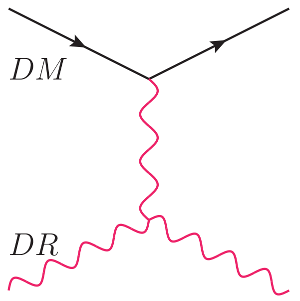
- The precise form of the scattering term, $\langle\sigma c\rangle$, is fully determined by the underlying microscopic or particle physics model, for example

IR behaviour

  - electron-photon, $\langle\sigma c\rangle \sim 1/m^2$
    Thomson scattering



  - DM-radiation with massive mediator, $\langle\sigma c\rangle \sim T^2/m^4$
    Boehm *et al*(astro-ph/0410591,1309.7588)



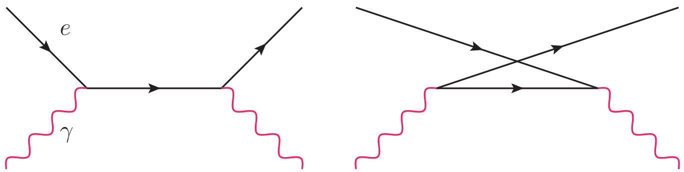
  - non-Abelian radiation, $\langle\sigma c\rangle \sim 1/T^2$
    Schmaltz et al(2015), 1507.04351,1505.03542

Relation to Particle Physics

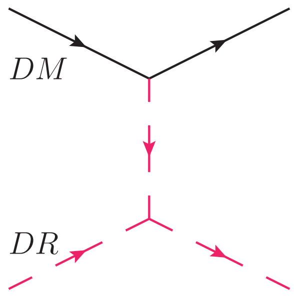
- The precise form of the scattering term, $\langle \sigma c \rangle$, is fully determined by the underlying microscopic or particle physics model, for example

IR behaviour

  - electron-photon, $\langle \sigma c \rangle \sim 1/m^2$
    Thomson scattering



  - DM-radiation with massive mediator, $\langle \sigma c \rangle \sim T^2/m^4$
    Boehm *et al*(astro-ph/0410591,1309.7588)



  - non-Abelian radiation, $\langle \sigma c \rangle \sim 1/T^2$
    Schmaltz et al(2015), 1507.04351,1505.03542

  - (pseudo-)scalar radiation, $\langle \sigma c \rangle \sim 1/T^2$, μ^2/T^4, T^2/μ^4
    Y.Tang,1603.00165(PLB)

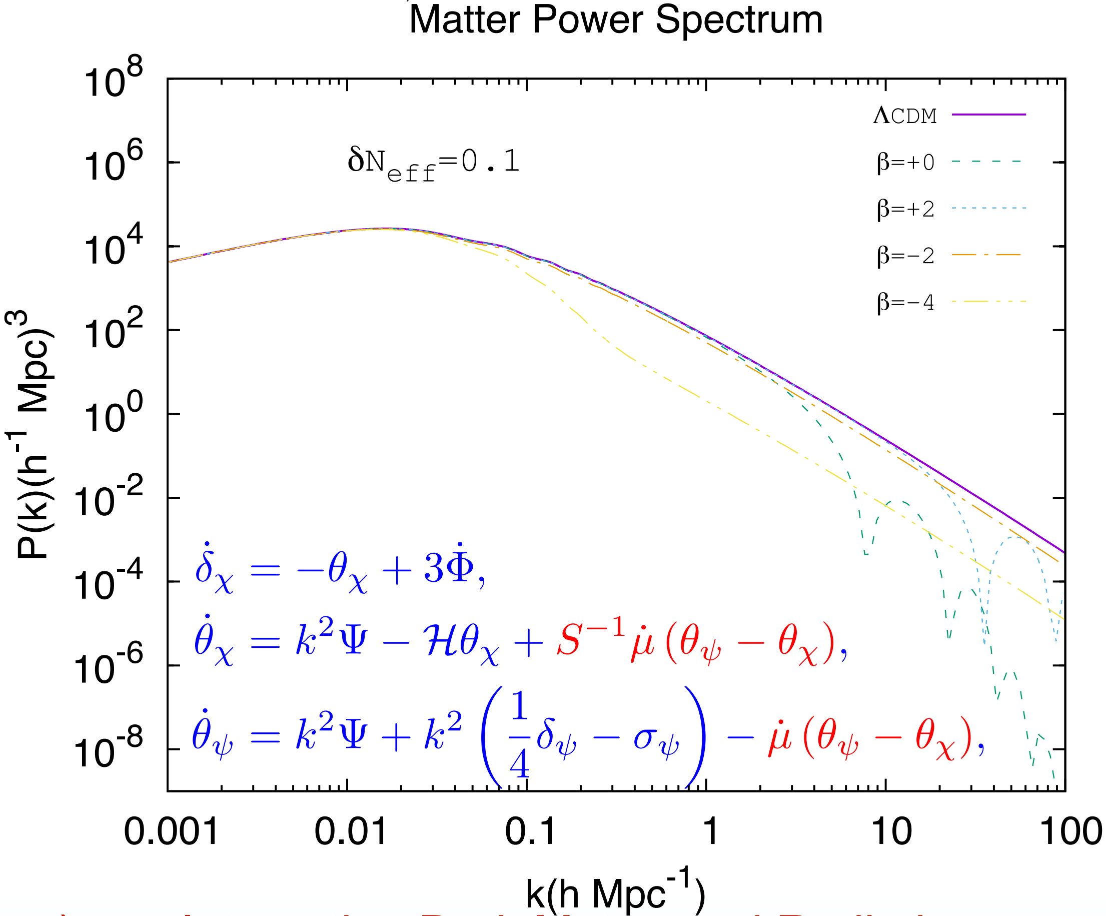
Effects on LSS

Parametrize the cross section ratio

Y.Tang,1603.00165(PLB)

$$u_0 \equiv \left[\frac{\sigma_{\chi\psi}}{\sigma_{\rm Th}}\right]\left[\frac{100{\rm GeV}}{m_\chi}\right], u_\beta(T) = u_0\left(\frac{T}{T_0}\right)^\beta,$$

where $\sigma_{\rm Th}$ is the Thomson cross section, $0.67\times10^{-24}{\rm cm}^{-2}$.



$$\dot\delta_\chi = -\theta_\chi + 3\dot\Phi,$$

$$\dot\theta_\chi = k^2\Psi - \mathcal{H}\theta_\chi + S^{-1}\dot\mu\,(\theta_\psi - \theta_\chi),$$

$$\dot\theta_\psi = k^2\Psi + k^2\left(\frac{1}{4}\delta_\psi - \sigma_\psi\right) - \dot\mu\,(\theta_\psi - \theta_\chi),$$

A Light Dark Photon

- Lagrangian

P.Ko, ***YT***, *1608.01083(PLB)*

$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi + \bar{\chi}\left(i\not{D} - m_\chi\right)\chi + \bar{\psi} i \not{D} \psi$$
$$- \left(y_\chi \Phi^\dagger \bar{\chi}^c \chi + y_\psi \Phi \bar{\psi} N + h.c.\right) - V(\Phi, H),$$

- DM χ (+1), dark radiation ψ(+2), scalar(+2)
- *U(1)* symmetry (*unbroken*), massless dark photon V_μ
- Φ is responsible for the DM relic density

$$\Omega h^2 \simeq 0.1 \times \left(\frac{y_\chi}{0.7}\right)^{-4} \left(\frac{m_\chi}{\text{TeV}}\right)^2 .$$

- Φ can decay into ψ and *N*.

Dark Radiation δN_{eff}

- Effective Number of Neutrinos, N_{eff}

$$\rho_R = \left[1 + N_{\rm eff} \times \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]\rho_\gamma,$$

$$\rho_\gamma \propto T_\gamma^4$$

- In SM cosmology, N_{eff} =3.046, Neutrinos decouple around MeV, and then stream freely.
- Cosmological bounds

Joint CMB+BBN, 95% CL preferred ranges *Planck 2015, arXiv:1502.01589*

$$N_{\rm eff} = \begin{cases} 3.11^{+0.59}_{-0.57} & \text{He+}\textit{Planck}\text{ TT+lowP,} \\ 3.14^{+0.44}_{-0.43} & \text{He+}\textit{Planck}\text{ TT+lowP+BAO,} \\ 2.99^{+0.39}_{-0.39} & \text{He+}\textit{Planck}\text{ TT,TE,EE+lowP,} \end{cases}$$

Constraint on New Physics

$$\left.\begin{array}{r} N_{\rm eff} < 3.7 \\ m^{\rm eff}_{\nu,\,\rm sterile} < 0.52\ \text{eV} \end{array}\right\} \text{95\%, } \textit{Planck}\text{ TT+lowP+lensing+BAO.}$$

Dark Radiation δN_{eff}

- Massless dark photon and fermion will contribute

$$\delta N_{\rm eff} = \left(\frac{8}{7}+2\right)\left[\frac{g_{*s}\left(T_\nu\right)}{g_{*s}\left(T^{\rm dec}\right)}\frac{g_{*s}^D\left(T^{\rm dec}\right)}{g_{*s}^D\left(T_D\right)}\right]^{\frac{4}{3}},$$

where T_ν is neutrino's temperature,

g_{*s} counts the effective number of dof for entropy density in SM,

g_{*s}^D denotes the effective number of dof being in kinetic equilibrium with V_μ.

For instance, when $T^{\rm dec} \gg m_t \simeq 173{\rm GeV}$ for $|\lambda_{\Phi H}| \sim 10^{-6}$, we can estimate $\delta N_{\rm eff}$ at the BBN epoch as

$$\delta N_{\rm eff} = \frac{22}{7}\left[\frac{43/4}{427/4}\frac{11}{9/2}\right]^{\frac{4}{3}} \simeq 0.53, \qquad (1)$$

δN_{eff}=0.4~1 for relaxing tension in Hubble constant

Scattering Cross Section

The averaged cross section $\langle\sigma_{\chi\psi}\rangle$ can be estimated from the squared matrix element for $\chi\psi \to \chi\psi$:

$$\overline{|\mathcal{M}|^2} \equiv \frac{1}{4}\sum_{\text{pol}} |\mathcal{M}|^2 = \frac{2g_X^4}{t^2}\left[t^2 + 2st + 8m_\chi^2 E_\psi^2\right], \quad (9)$$

where the Mandelstam variables are $t = 2E_\psi^2(\cos\theta - 1)$ and $s = m_\chi^2 + 2m_\chi E_\psi$, where θ is the scattering angle, and E_ψ is the energy of incoming ψ in the rest frame of χ. Integrated with a temperature-dependent Fermi-Dirac distribution for E_ψ, we find that $\langle\sigma_{\chi\psi}\rangle$ goes roughly as $g_X^4/(4\pi T_D^2)$.

- *In general, the cross section could have different temperature dependence, depending on the underlying particle models.*

Numerical Results

We take the central values of six parameters of ΛCDM from `Planck`,

$\Omega_b h^2 = 0.02227,$	Baryon density today
$\Omega_c h^2 = 0.1184,$	CDM density today
$100\theta_{\rm MC} = 1.04106,$	$100 \times$ approximation to r_*/D_A
$\tau = 0.067,$	Thomson scattering optical depth
$\ln\left(10^{10} A_s\right) = 3.064,$	Log power of primordial curvature perturbations
$n_s = 0.9681,$	Scalar Spectrum power-law index

which gives $\sigma_8 = 0.817$ in vanilla ΛCDM cosmology.

With the same input as above, now take

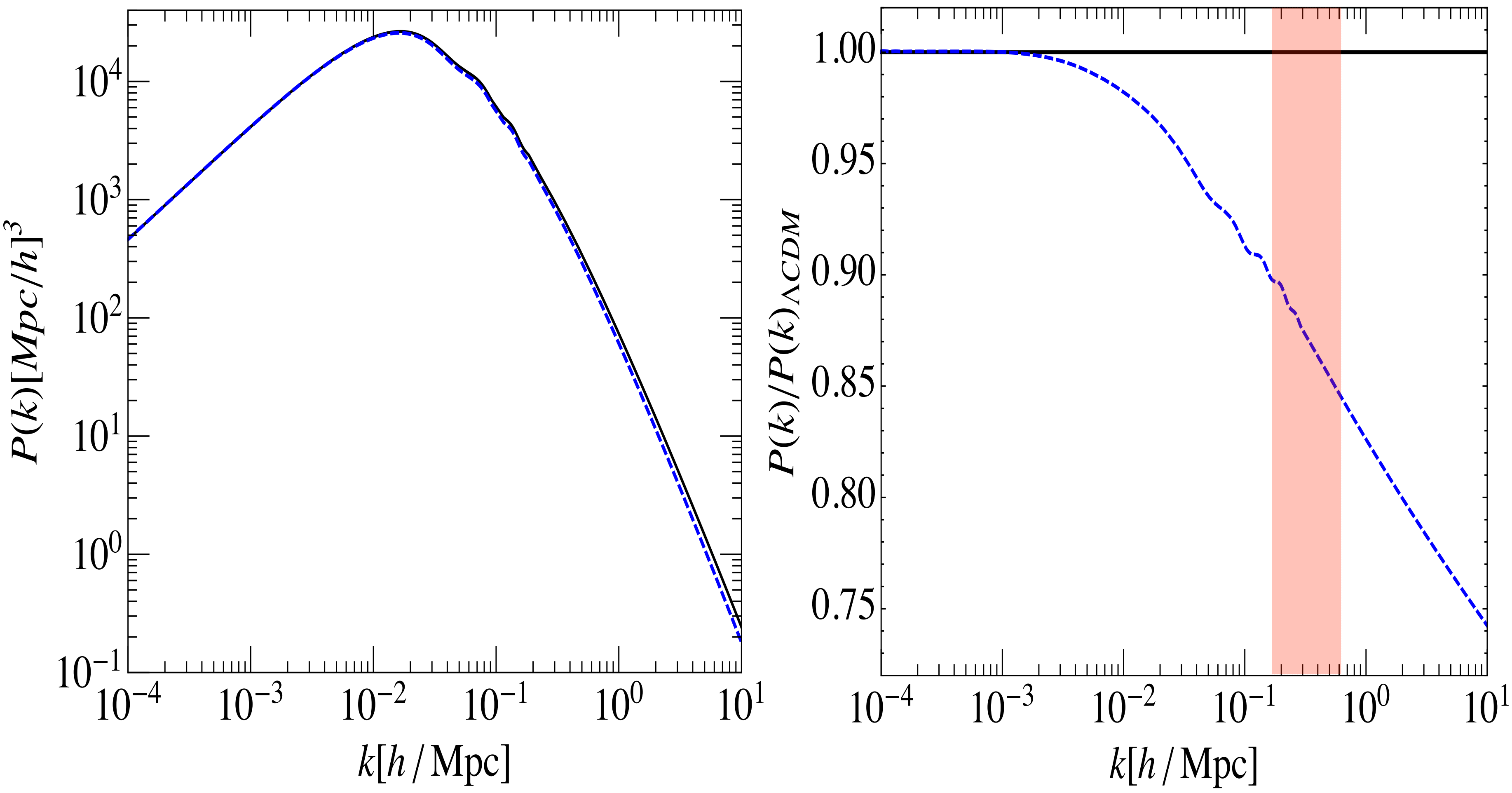
$$\delta N_{\rm eff} \simeq 0.53, m_\chi \simeq 100 \text{GeV and } g_X^2 \simeq 10^{-8}$$

in the interacting DM case, we have $\sigma_8 \simeq 0.744$.

Modified Boltzmann code ***CLASS*(*Blas&Lesgourgues&Tram*)**

Matter Power Spectrum

DM-DR scattering causes diffuse damping at relevant scales, resolving σ_8 problem



Residual Non-Abelian DM&DR

P.Ko&**YT**, 1609.02307

- Consider *SU(N)* Yang-Mills gauge fields and a Dark Higgs field Φ

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - \lambda_\phi\left(|\Phi|^2 - v_\phi^2/2\right)^2,$$

- Take *SU(3)* as an example,

$$A^a_\mu t^a = \frac{1}{2}\begin{pmatrix} A^3_\mu + \frac{1}{\sqrt{3}}A^8_\mu & A^1_\mu - iA^2_\mu & A^4_\mu - iA^5_\mu \\ A^1_\mu + iA^2_\mu & -A^3_\mu + \frac{1}{\sqrt{3}}A^8_\mu & A^6_\mu - iA^7_\mu \\ A^4_\mu + iA^5_\mu & A^6_\mu + iA^7_\mu & -\frac{2}{\sqrt{3}}A^8_\mu \end{pmatrix}.$$

- *SU(3)* → *SU(2)*

$$\langle\Phi\rangle = \begin{pmatrix} 0 & 0 & \frac{v_\phi}{\sqrt{2}} \end{pmatrix}^T, \Phi = \begin{pmatrix} 0 & 0 & \frac{v_\phi + \phi(x)}{\sqrt{2}} \end{pmatrix}^T,$$

The massive gauge bosons $A^{4,\cdots,8}$ as dark matter obtain masses,

$$m_{A^{4,5,6,7}} = \frac{1}{2}gv_\phi,\ m_{A^8} = \frac{1}{\sqrt{3}}gv_\phi,$$

and massless gauge bosons $A^{1,2,3}_\mu$. The physical scalar ϕ can couple to $A^{4,\cdots,8}_\mu$ at tree level and to $A^{1,2,3}$ at loop level.

$SU(N) \rightarrow SU(N-1)$

- *2N-1* massive gauge bosons: Dark Matter
- *(N-1)²-1* massless gauge bosons: Dark Radiation
- mass spectrum

$$m_{A^{(N-1)^2,\ldots,N^2-2}} = \frac{1}{2} g v_\phi, \; m_{A^{N^2-1}} = \frac{\sqrt{N-1}}{\sqrt{2N}} g v_\phi,$$

This can be proved by looking at the structure of f^{abc}. Divide the generators t^a into two subset,

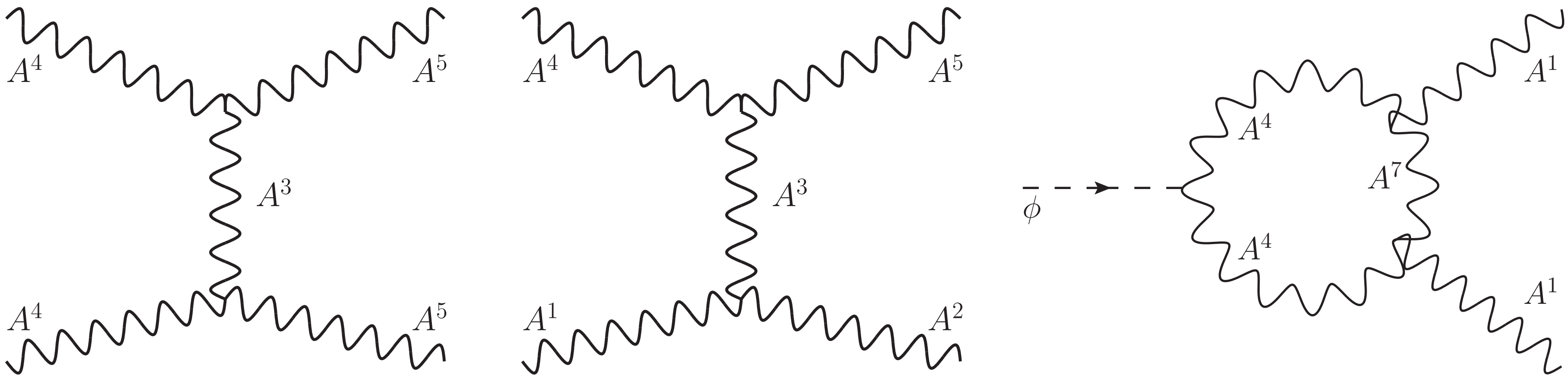
$$a \subset [1, 2, ..., (N-1)^2 - 1], a \subset [(N-1)^2, ..., N^2 - 1].$$

Since $[t^a, t^b] = i f^{abc} t^c$ for the first subset forms closed $SU(N-1)$ algebra, we have $f^{abc} = 0$ when only one of a, b and c is from the second subset. If one index is $N^2 - 1$, then other two must be among the second subset to give no vanishing f^{abc}, because t^{N^2-1} commutes with t^a from $SU(N-1)$.

Phenomenology

- Scattering and decay processes

P.Ko&**YT**, 1609.02307



- Constraints

$$\delta N_{\rm eff} = \frac{8}{7}\left[(N-1)^2 - 1\right] \times 0.055,$$

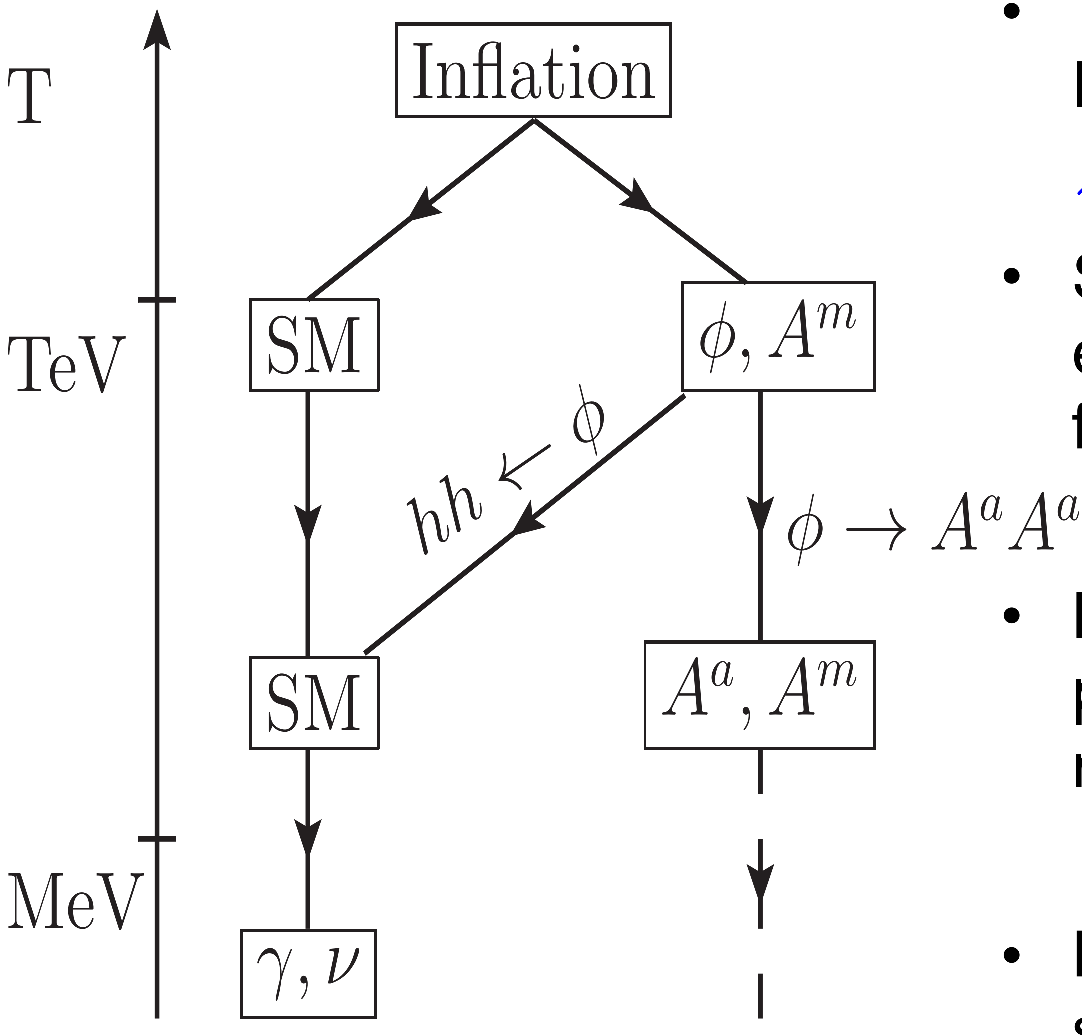
$$g^2 \lesssim \frac{T_\gamma}{T_A}\left(\frac{m_A}{M_P}\right)^{1/2} \sim 10^{-7},$$

$$\frac{m_A}{T_{\rm reh}} \sim \ln\left[\frac{\Omega_b M_P g^4}{\Omega_X m_p \eta}\right] \sim \mathcal{O}(30).$$

- ***N<6 if thermal***
- ***small coupling,***
- ***non-thermal production,***
- ***low reheating temperature***

Schmaltz et al(2015) EW charged DM

Thermal History



- The minimal setup with Higgs portal interaction $\lambda_{\phi H}\Phi^\dagger\Phi H^\dagger H$
- SM and DS are decoupled early, DM is produced by freeze-in mechanism
- Late time decay, entropy production due to non-relativistic decay, DR(δN_{eff})
- DM and DS scattering suppress the matter power spectrum

Summary

- We discussed some cosmological effects with *interacting* Dark Matter and Dark Radiation
- This scenario is motivated theoretically and also from observational tensions for CDM, H_0 and σ_8
- We present two particle physics models:
  - A massless dark photon with *unbroken U(1)* gauge symmetry
  - *Residual non-Abelian* Dark Matter and Dark Radiation
- It is possible to resolve tensions simultaneously

Thanks for your attention.