Interacting Dark Matter and Astrophysical Signatures

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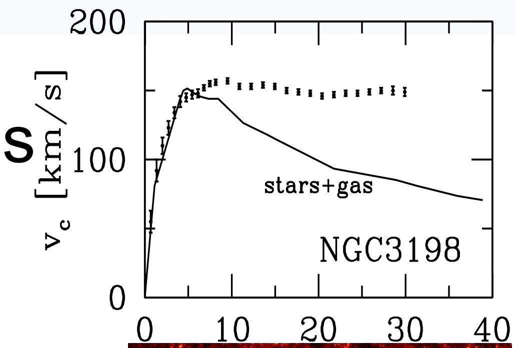
University of Pittsburgh, Oct 19-21, 2017

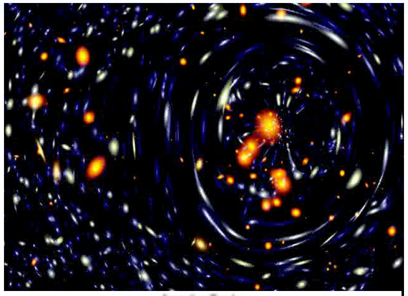
based on ***Tang*****,1603.00165,**
w**/Ko,1608.01083,1609.02307,**
w/Ko & Nagata,1706.05605

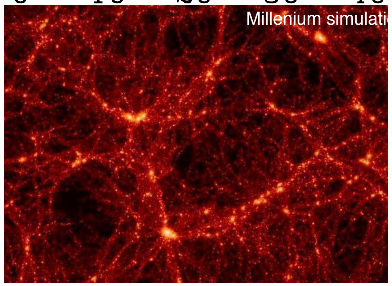
Contents

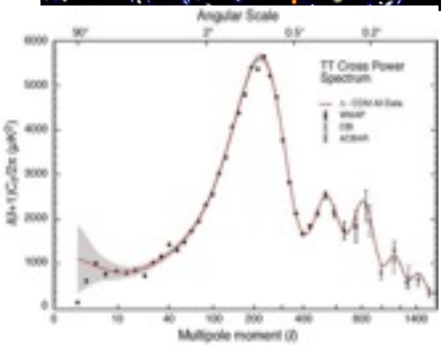
Evidence of Dark Matter

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



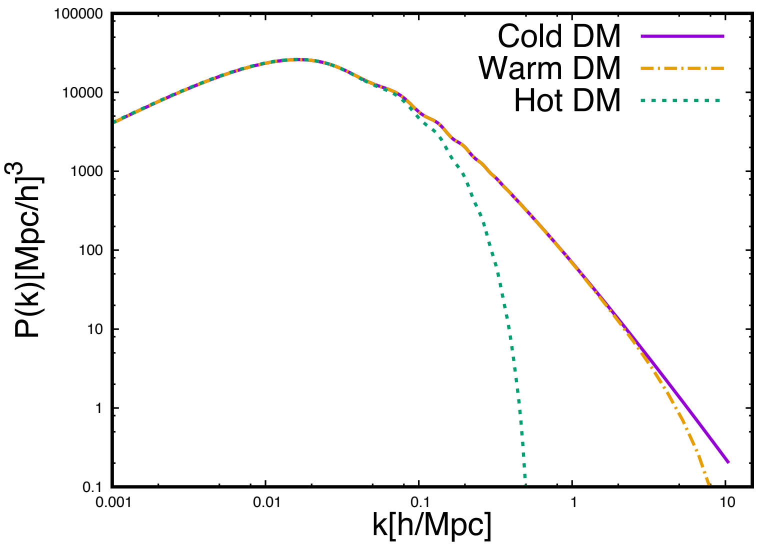






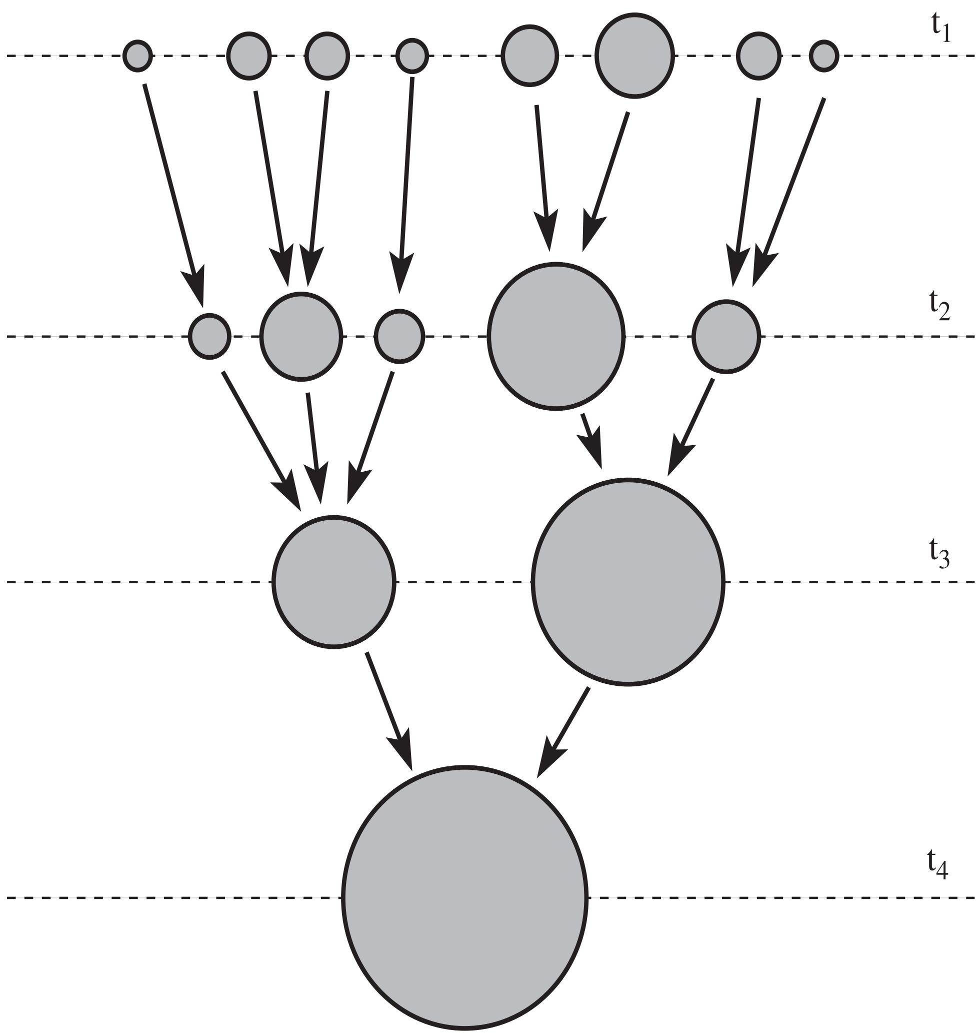
All ***confirmed*** *evidence comes from gravitational interaction*

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



Merger History of Dark Halo

- Standard picture
- DM halos grow hierarchically
- Small scale structures form first
- Then merge into larger halos



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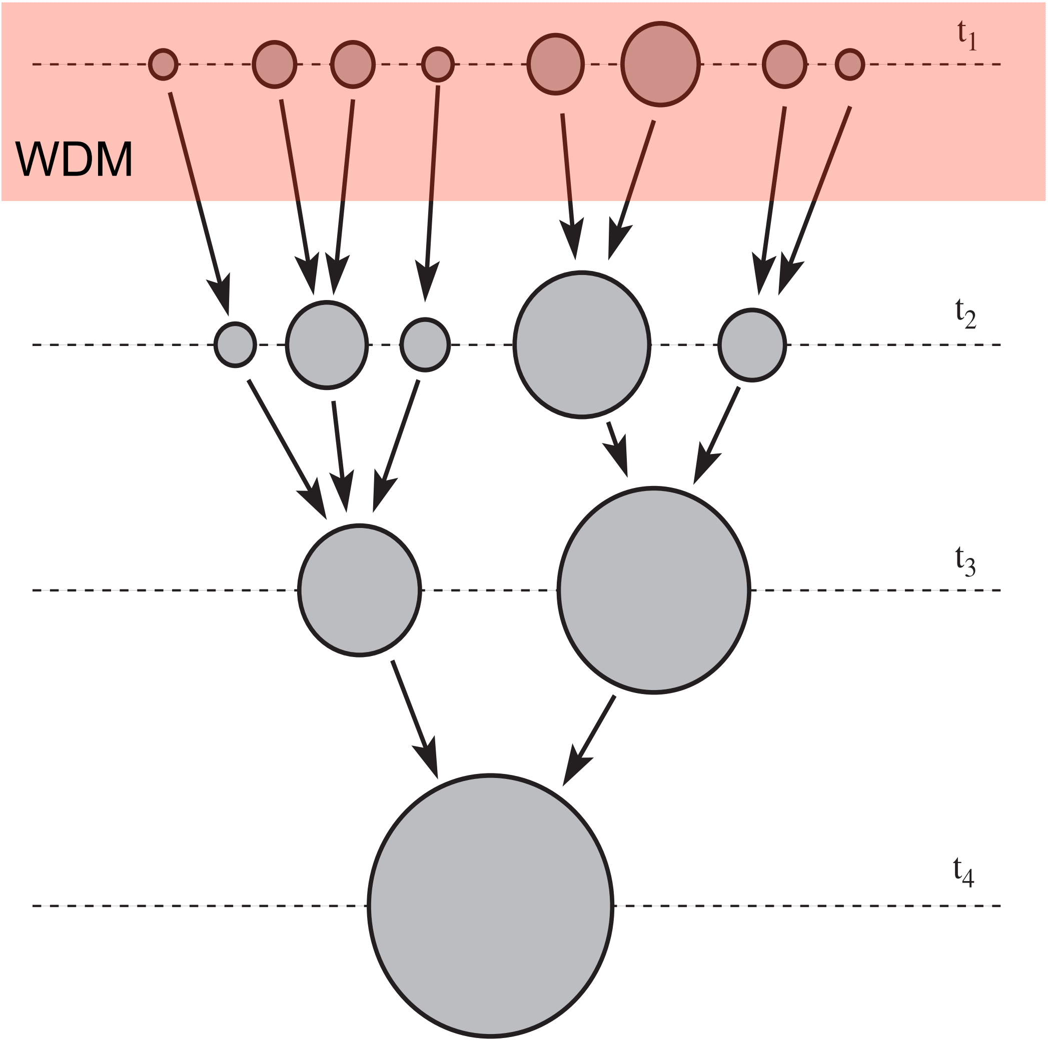

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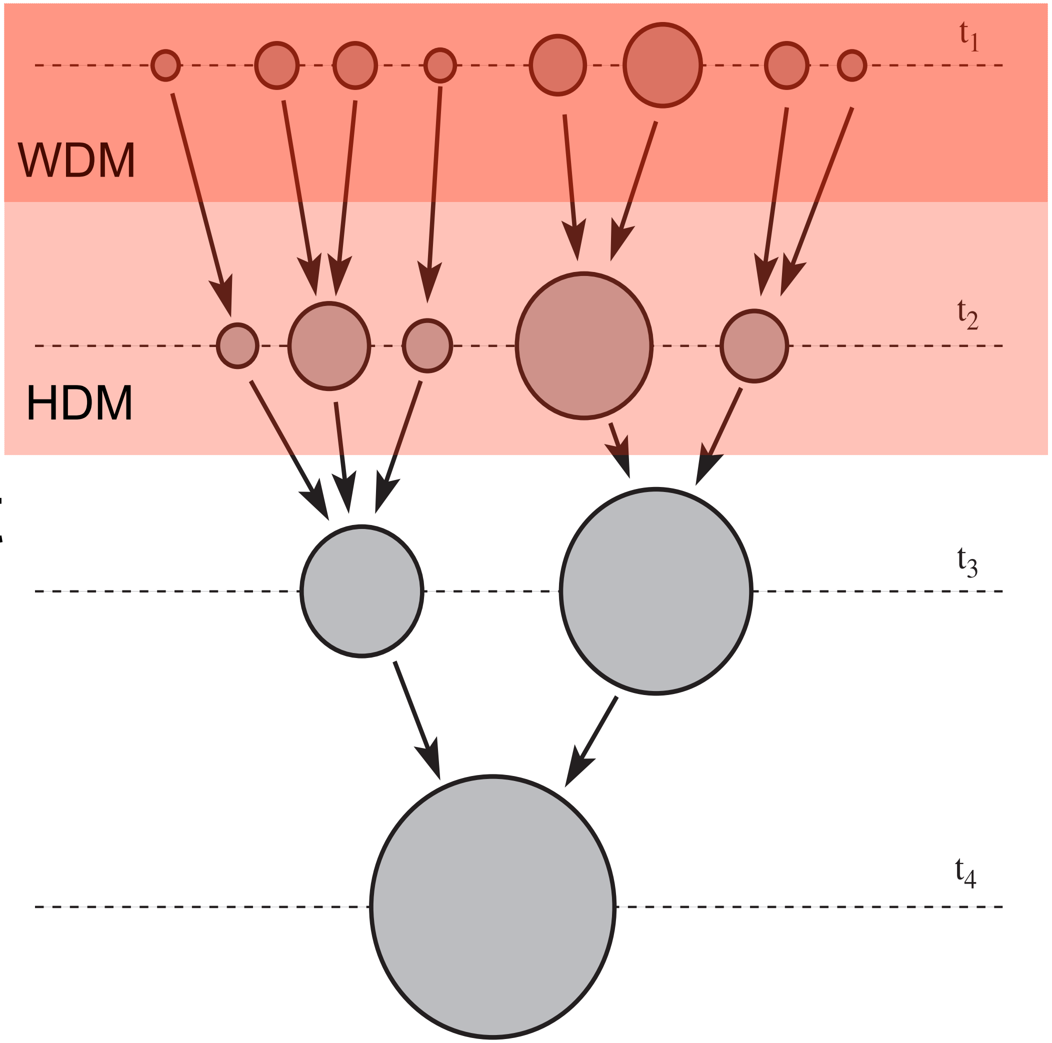
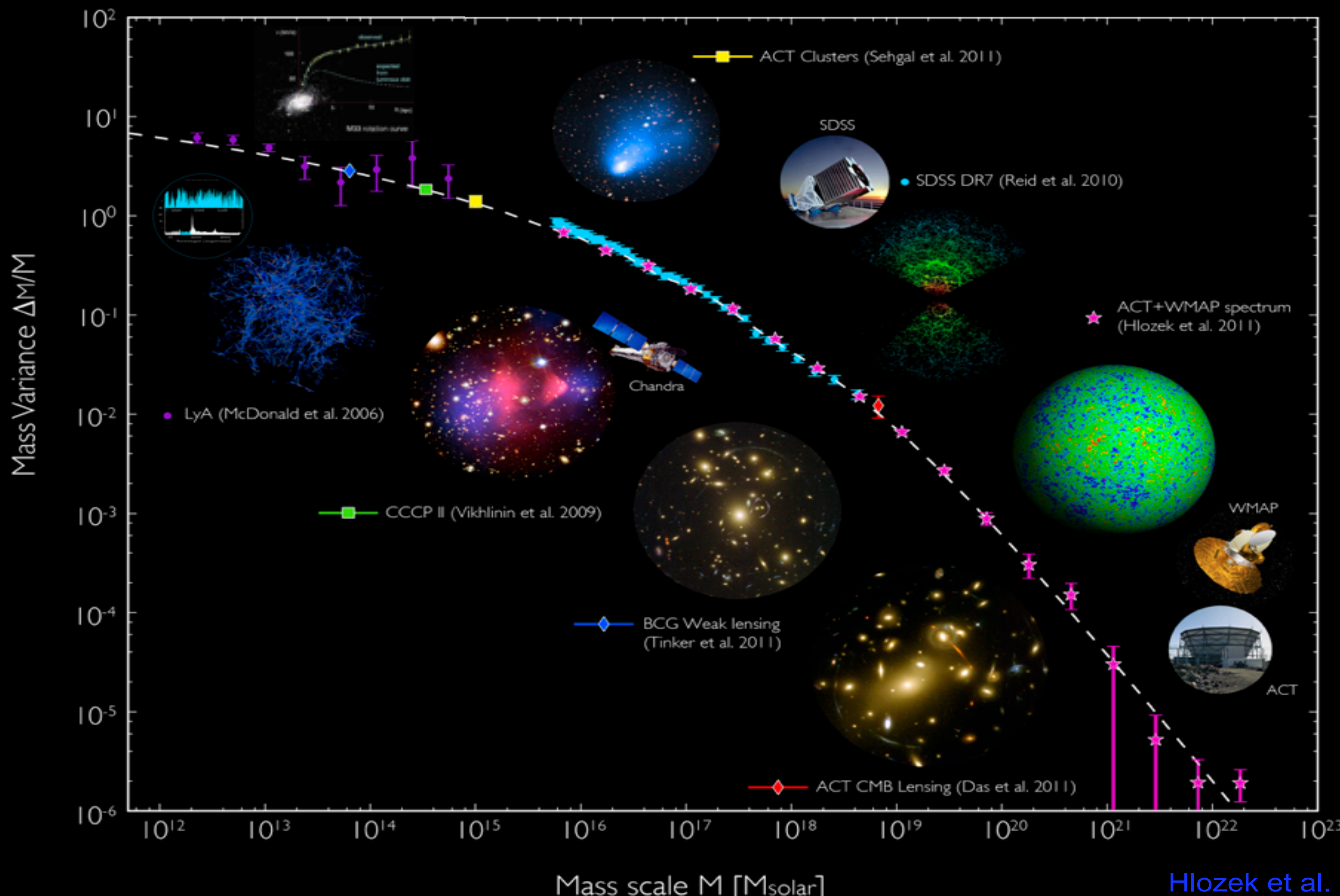
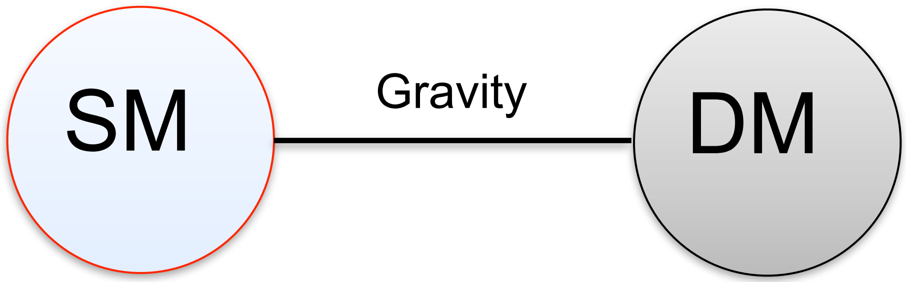


ΛCDM: successful on large scales



Hlozek et al. 2012

DM Scenarios



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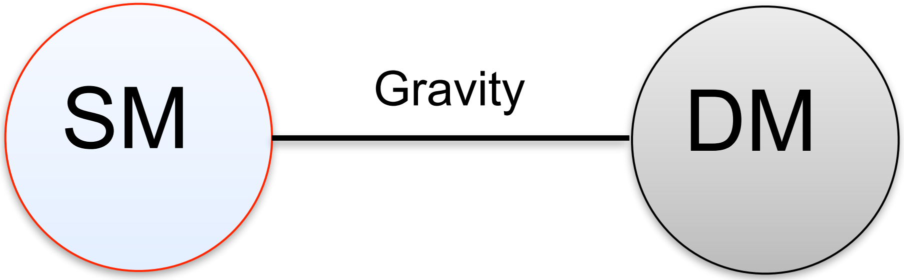

Ex: ***YT***&Wu, 1708.05138, 1606. 04701
and refs therein …….

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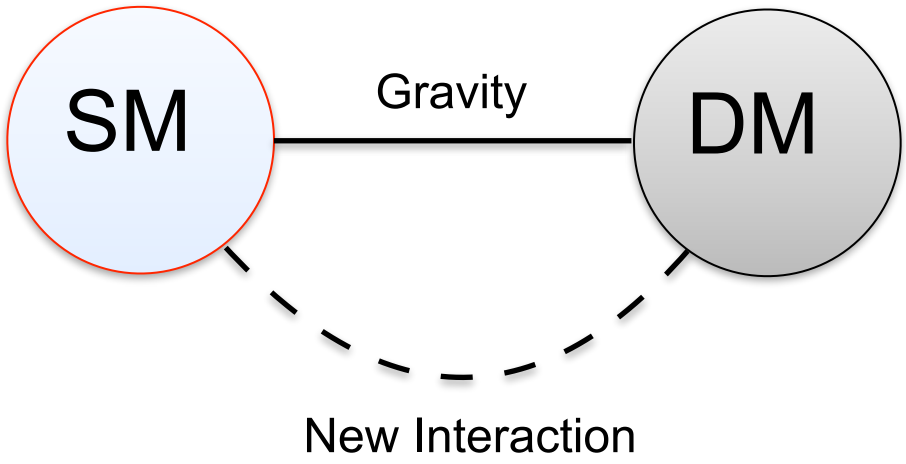

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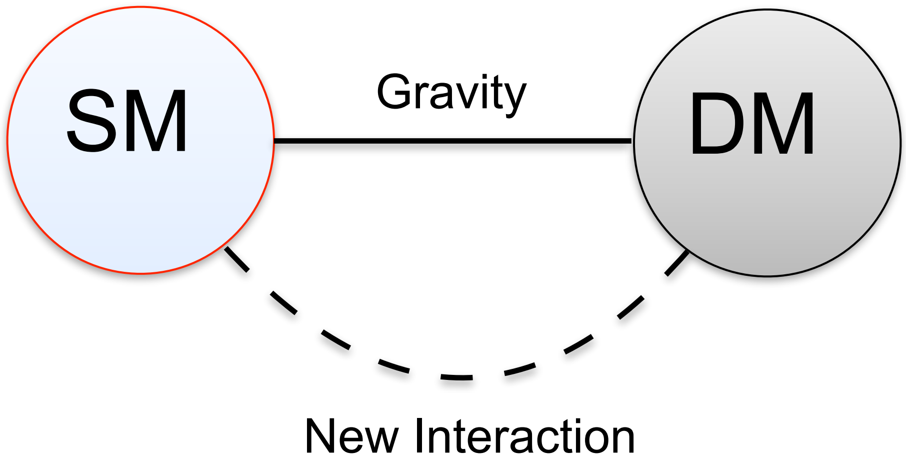
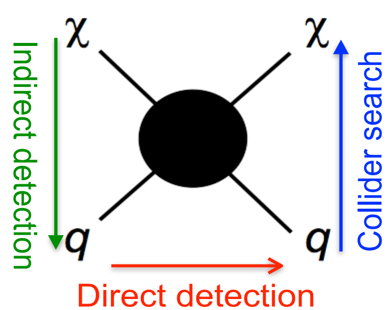


Weakly Interacting Massive Particle

- Mass around ~100GeV
- Coupling ~ 0.5
- Correct relic abundance Ω~0.3
- Searches for CDM
  - Collider qq > XXj
  - Direct Xq > Xq
  - Indirect XX > qq
- Theoretically interesting



- Supersymmetry
- Extra-dimension
- Sterile Neutrino
- Axion
- Wimpzilla
- Dark atom/pion/glueball
- Primordial black hole
- ……

Beyond Collisionless 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,SIMP $\frac{\sigma}{M_X} \sim \mathrm{cm}^2/\mathrm{g} \sim \mathrm{barn}/\mathrm{GeV}$
- 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? 3σ

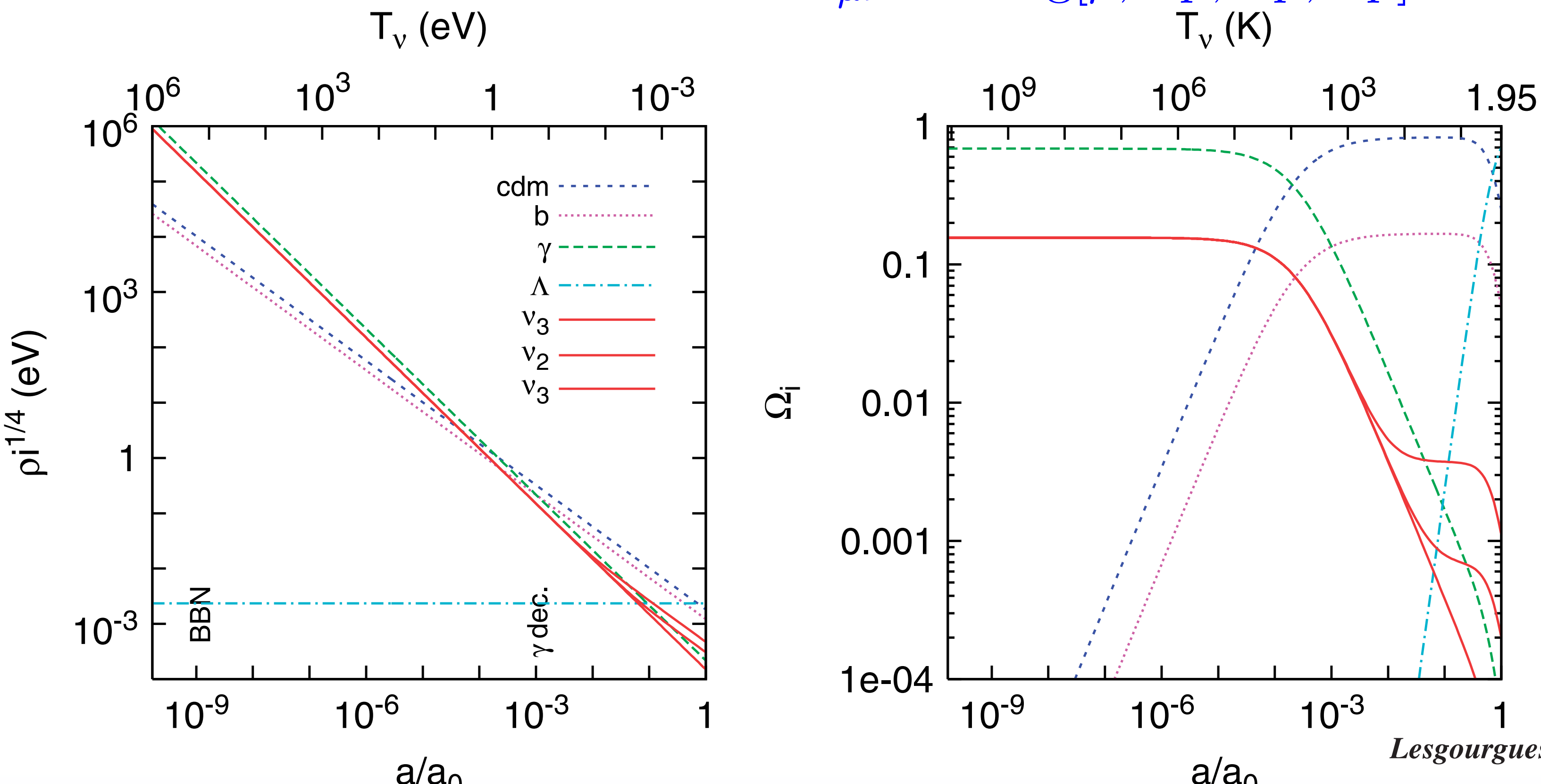
Cosmological History

- Einstein's equation

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

- Homogeneous&isotropy

$$g_{\mu\nu} = \mathrm{Diag}[1, -a^2, -a^2, -a^2]$$
$$T_{\mu\nu} = \mathrm{Diag}[\rho, -p, -p, -p]$$



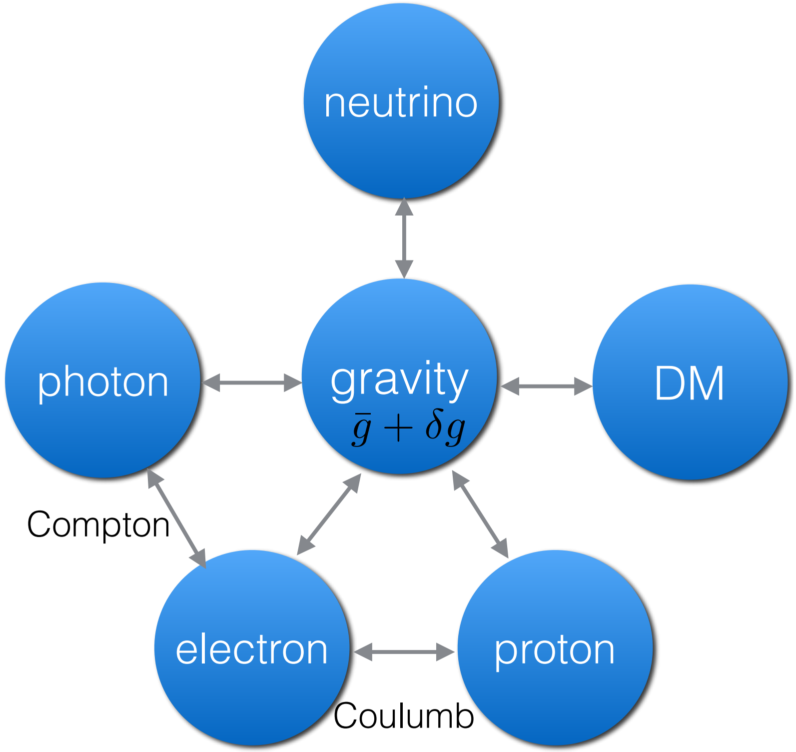
Lesgourgues, Pastor

Cosmological History

- Small perturbations (← Inflation)

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}, T_{\mu\nu} = \overline{T}_{\mu\nu} + \delta T_{\mu\nu},$$

- First-order perturbation of Boltzmann equation
  - anisotropy in CMB(δT)
  - matter power spectrum for LSS (δρ)
  - Primordial GW

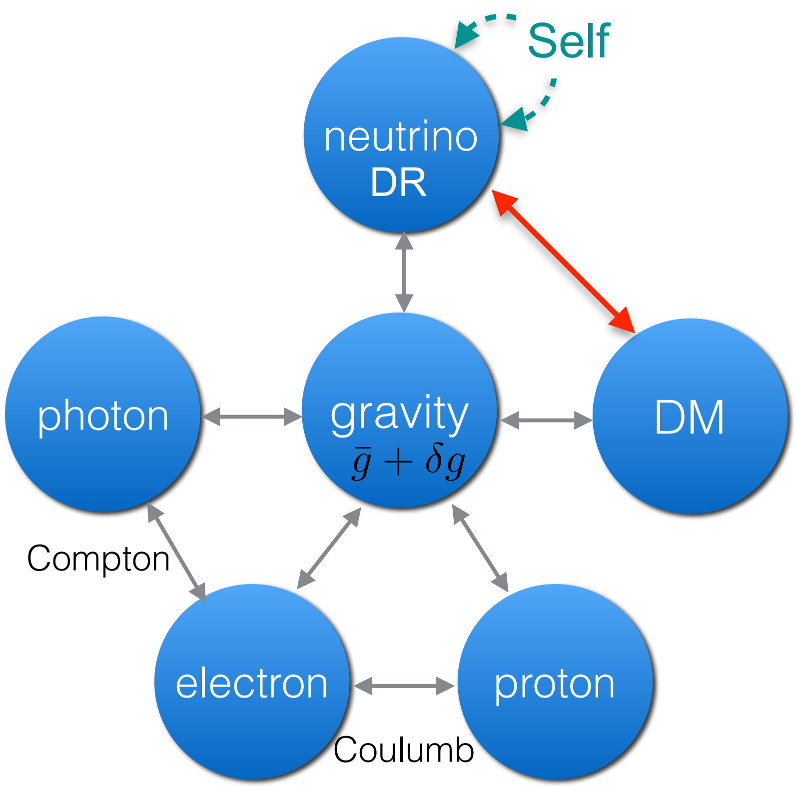


Modified Cosmological History

- Small perturbations (⟵ Inflation)

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}, T_{\mu\nu} = \overline{T}_{\mu\nu} + \delta T_{\mu\nu},$$

- First-order perturbation of Boltzmann equation
  - anisotropy in CMB(δT)
  - matter power spectrum for LSS (δρ)
  - Primordial GW
- (Self-)Interaction sometimes also matters



Interacting Radiation

- free-streaming

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

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

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

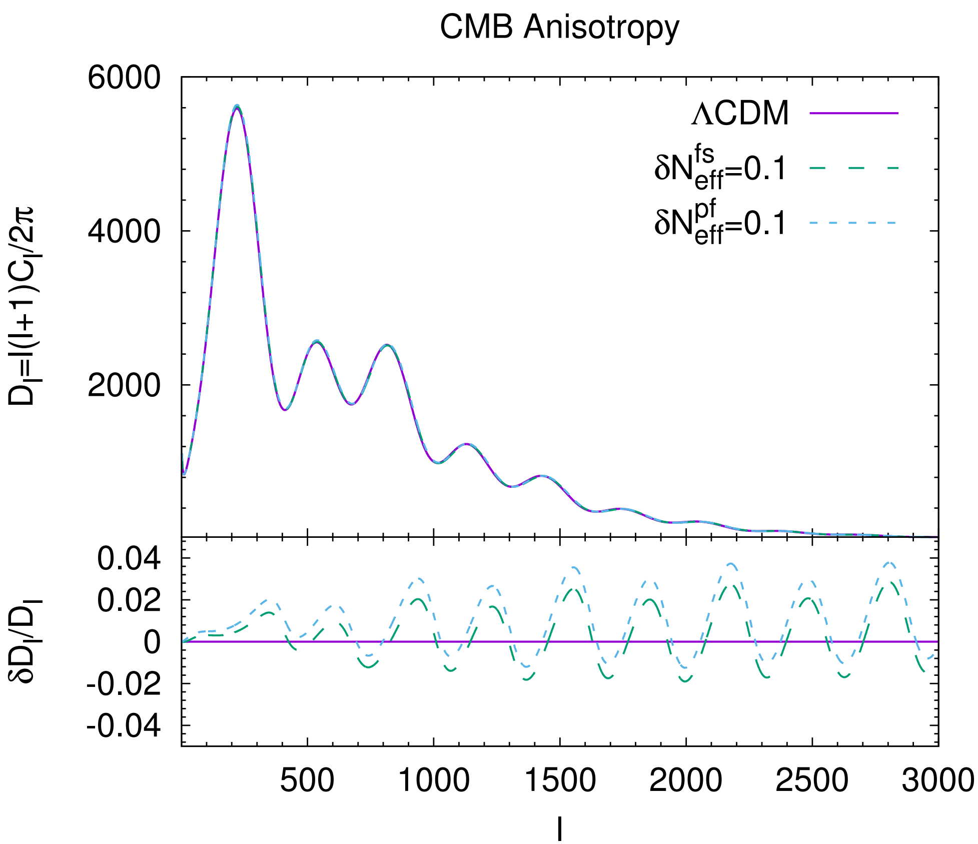
- perfect fluid $\Gamma \gg \mathcal{H}$

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

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

$\sigma_\nu=0$

Tang,1603.00165



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

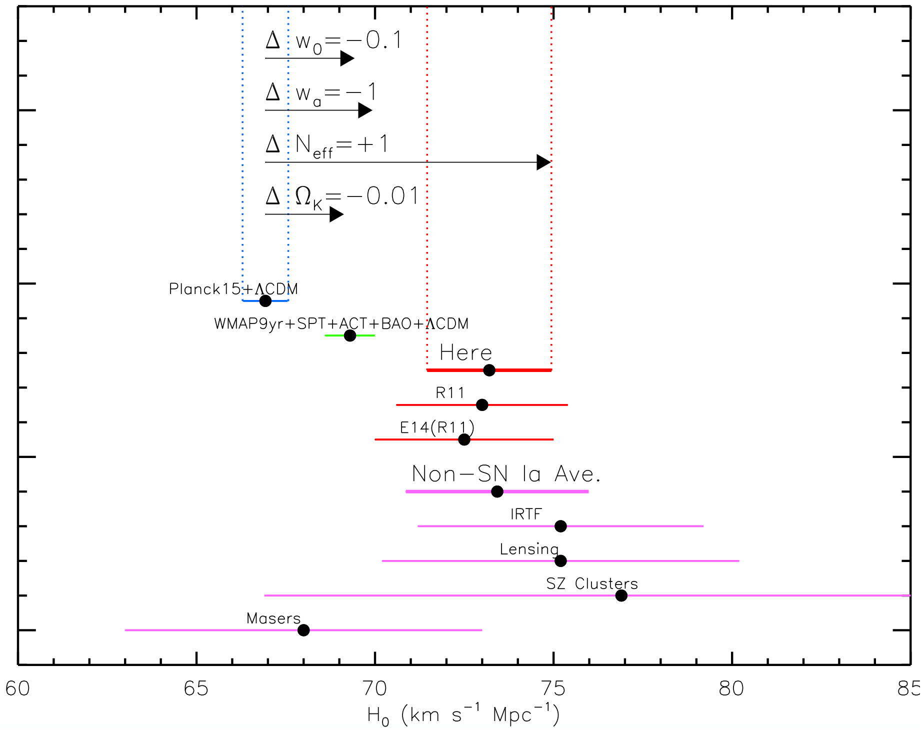
Tension in Hubble Constant?

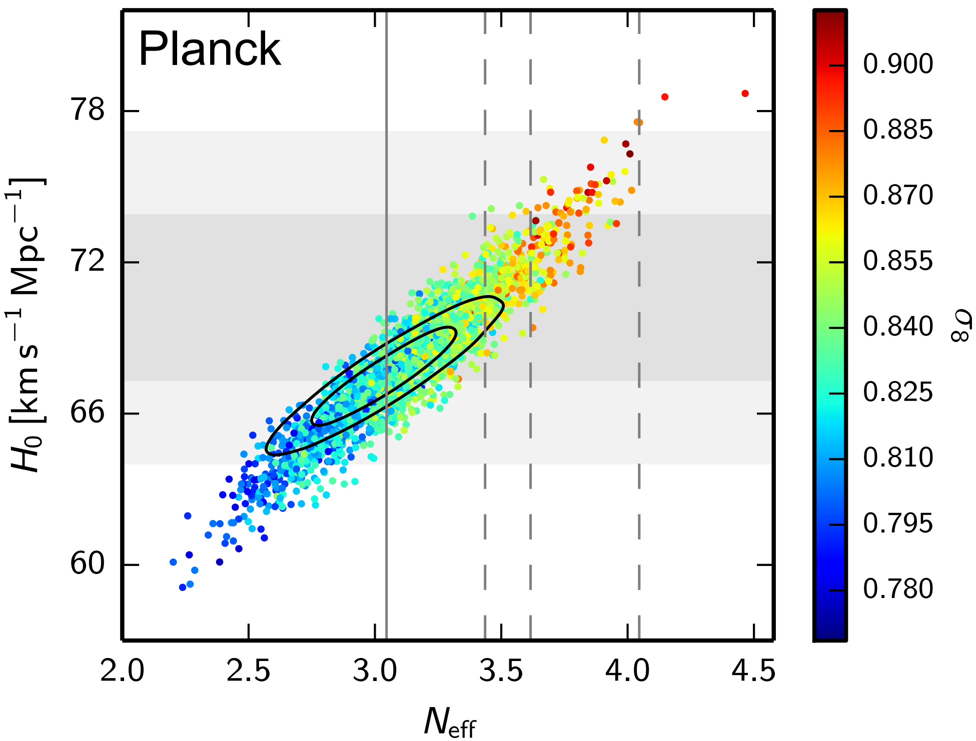
- Hubble Constant H_0 defined as the present value of

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

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

RIESS ET AL.





Tension in σ8 ?

- Variance of perturbation field → collapsed objects

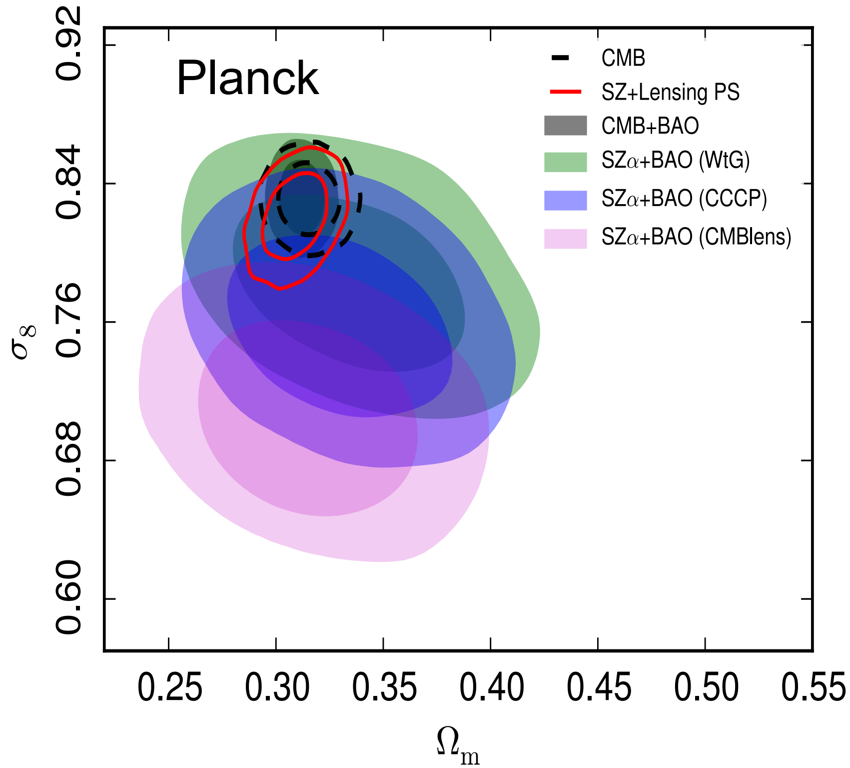
$$\delta(\boldsymbol{r}) = \frac{\rho(\boldsymbol{r}) - \bar{\rho}}{\bar{\rho}}, \sigma^2(r) = \langle \delta(\boldsymbol{x})\delta(\boldsymbol{x}-\boldsymbol{r})\rangle$$

$$\delta(\boldsymbol{k}) = \frac{1}{(2\pi)^3}\int \delta(\boldsymbol{r}) e^{-i\boldsymbol{k}\cdot\boldsymbol{r}} d^3\boldsymbol{r}, P(k) = \langle|\delta(\boldsymbol{k})|^2\rangle$$

- *P*(*k*): matter power spectrum

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

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



Tension in σ8 ?

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

Diffusion Damping

CMB Silk damping

- *Dark Matter* scatters with *radiation*, which induces new contributions in the cosmological perturbation equations, ex: Ma&Bertschinger, Boehm et al, ETHOS…

$$\dot{\delta}_\chi = -\theta_\chi + 3\dot{\Phi},$$

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

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

$$\frac{S^{-1}\dot{\mu}}{\mathcal{H}} \sim 1$$

If $\sigma \sim \frac{g_X^4}{T_D^2} \Rightarrow g_X^2 \sim \frac{T_\gamma}{T_D}\sqrt{\frac{m_\chi}{M_{pl}}}$

where dot means derivative over conformal time $d\tau \equiv dt/a$ (a is the scale factor), θ_ψ and θ_χ are velocity divergences of radiation ψ and DM χ's, k is the comoving wave number, Ψ is the gravitational potential, δ_ψ and σ_ψ are the density perturbation and the anisotropic stress potential of ψ, and $\mathcal{H} \equiv \dot{a}/a$ is the conformal Hubble parameter. Finally, the scattering rate and the density ratio are defined by $\dot{\mu} = a n_\chi \langle\sigma_{\chi\psi} c\rangle$ and $S = 3\rho_\chi/4\rho_\psi$, respectively.

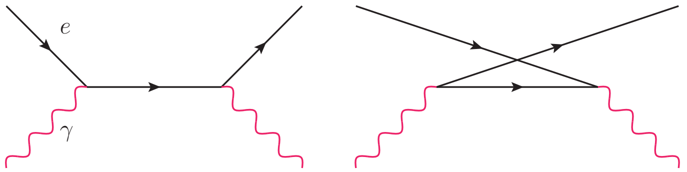
Relation to Particle Physics

- 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, $<\sigma c> \sim 1/m^2$

    Thomson scattering



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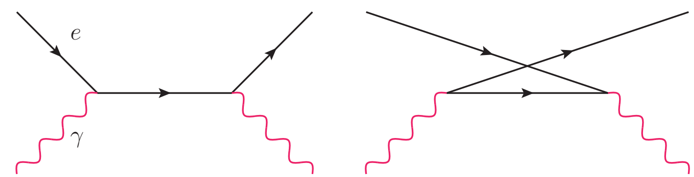
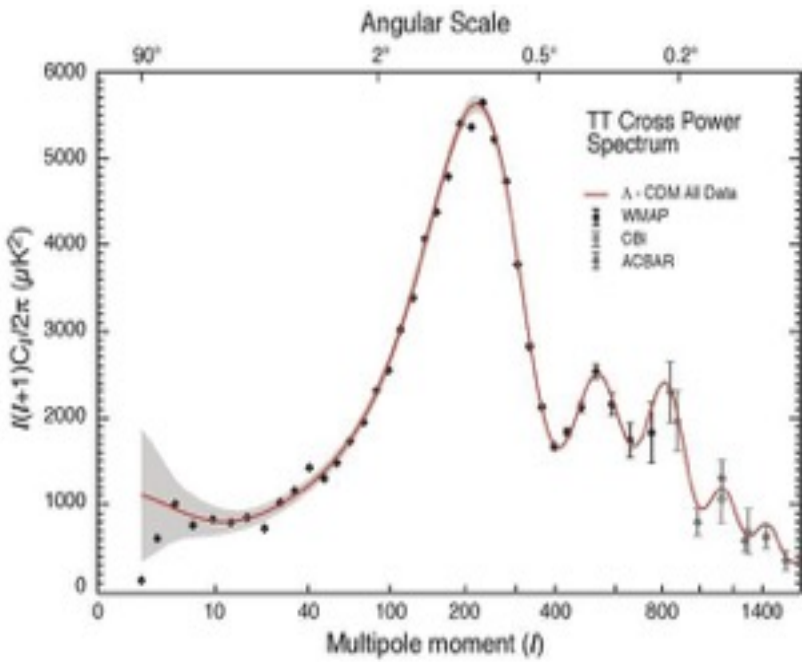
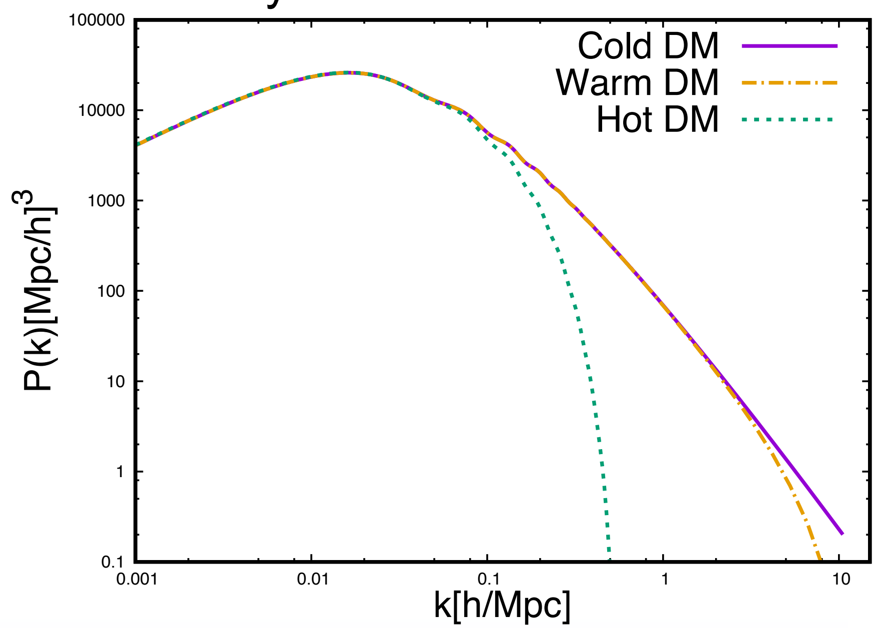




baryonic acoustic oscillations



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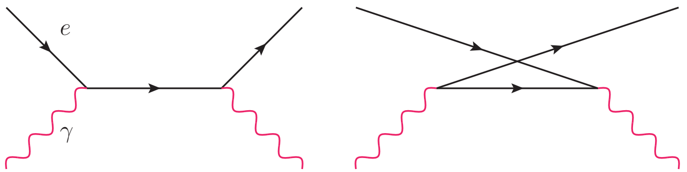
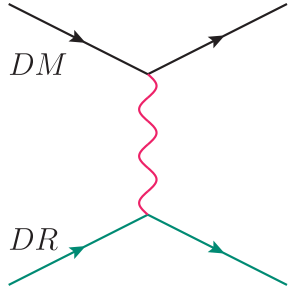


  - DM-radiation with massive mediator, $\langle\sigma c\rangle \sim T^2/m^4$



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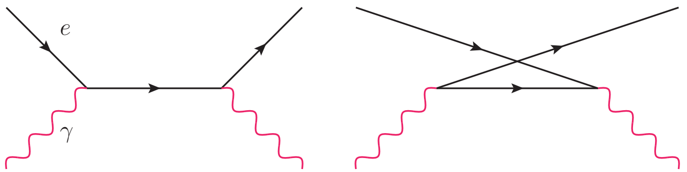

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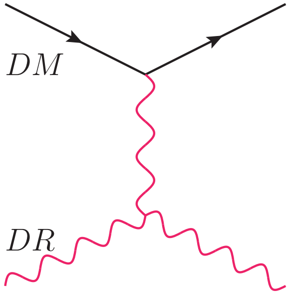

  - non-Abelian radiation, $\langle\sigma c\rangle \sim 1/T^2$
    Schmaltz et al(2015), 1507.04351,1505.03542

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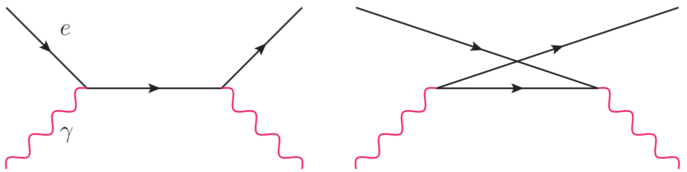

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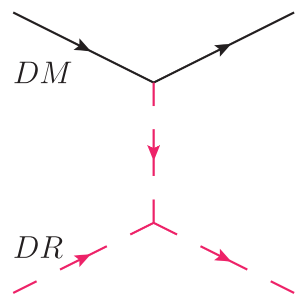


  - non-Abelian radiation, $\langle \sigma c \rangle \sim 1/T^2$
    Schmaltz et al(2015), 1507.04351,1505.03542
  - (pseudo-)scalar radiation, $\langle \sigma c \rangle \sim 1/T^2$, μ^2/T^4, T^2/m^4
    Tang,1603.00165

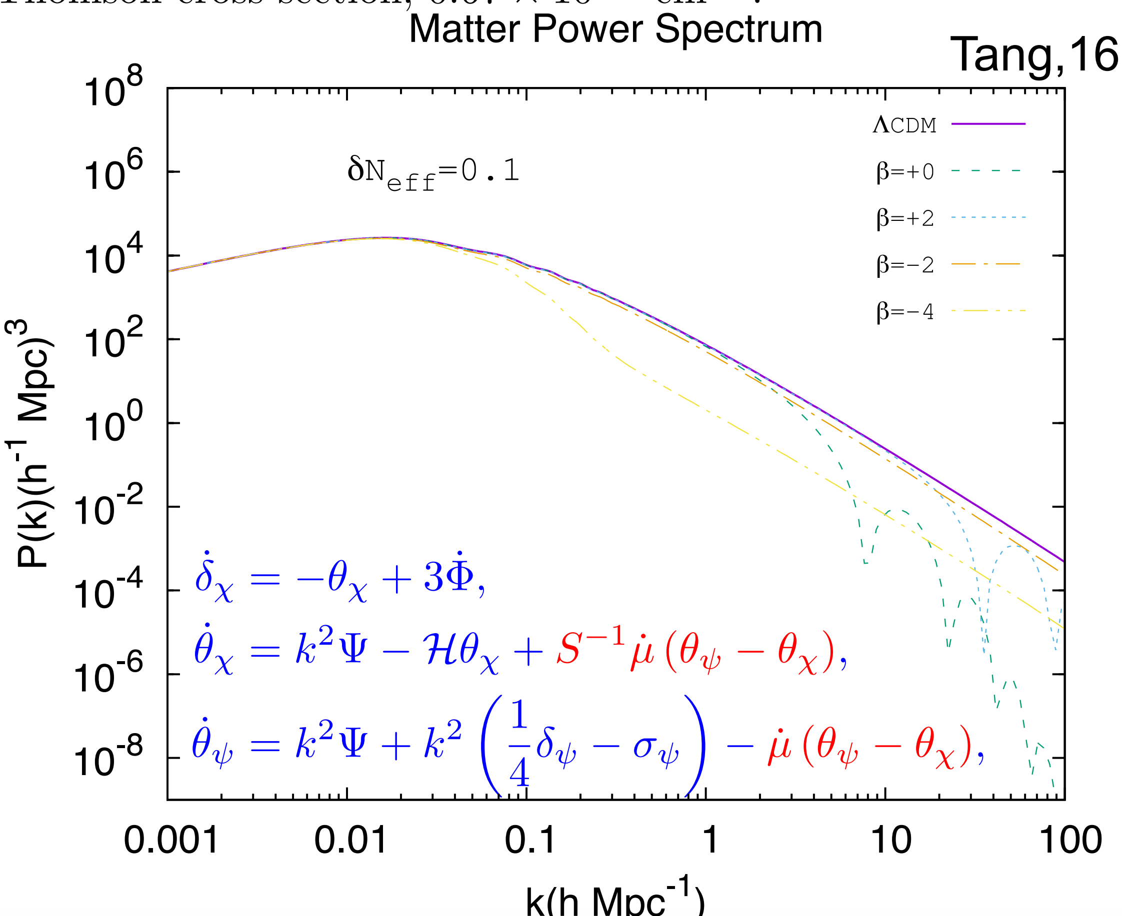
Effects on LSS

Parametrize the cross section ratio

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

where $\sigma_{\rm Th}$ is the Thomson cross section, $0.67 \times 10^{-24}\text{cm}^{-2}$.

Tang,1603.00165



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A Light Dark Photon

Ko&***Tang***, *1608.01083*

- Lagrangian

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

$$- \left(y_\chi\Phi^\dagger\bar{\chi}^c\chi + y_\psi\Phi\bar{\psi}N + h.c.\right) - V(\Phi, H),$$

- 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

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

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 $\chi\psi \to \chi\psi$:

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

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

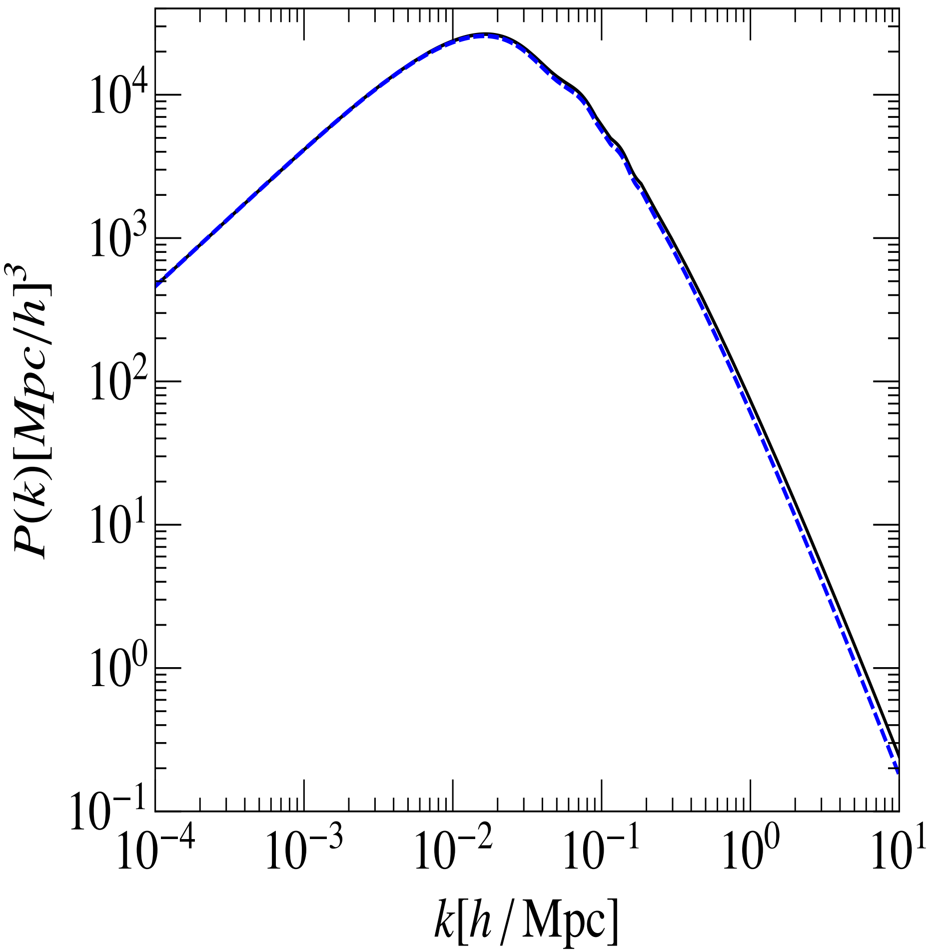
$$\delta N_{\rm eff} \simeq 0.53, m_\chi \simeq 100 {\rm GeV} \text{ and } g_X^2 \simeq 10^{-8}$$

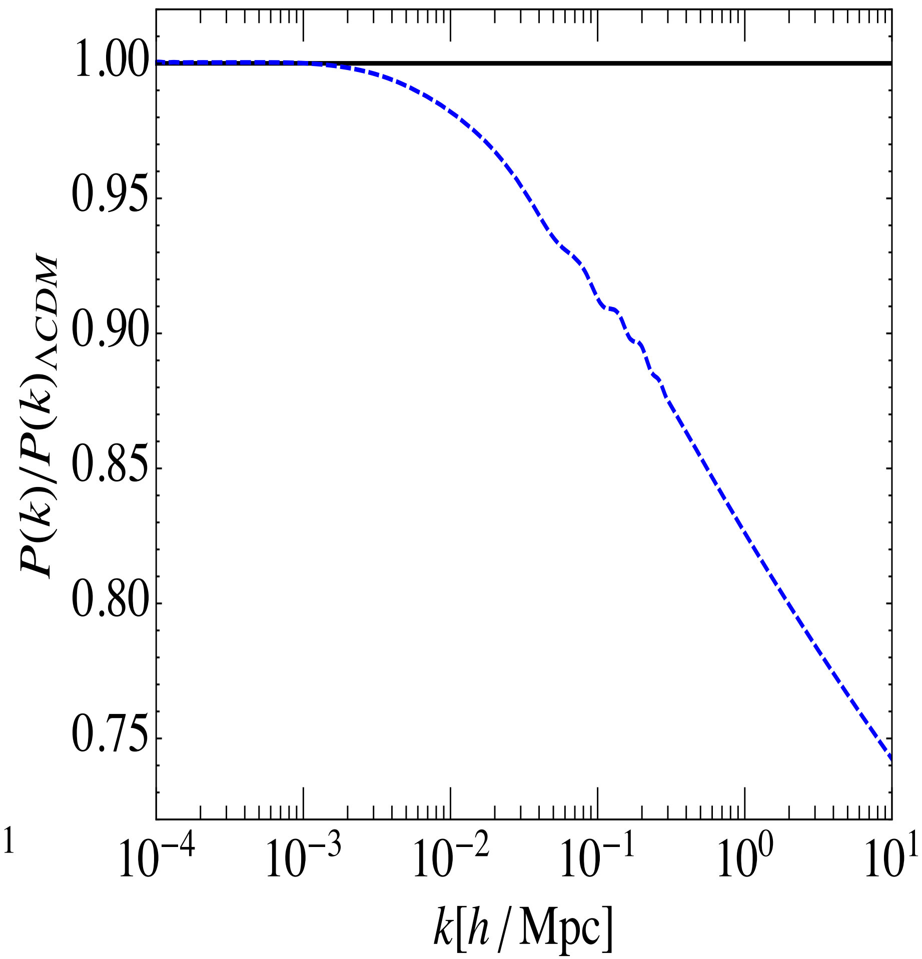
in the interacting DM case, we have $\sigma_8 \simeq 0.744$.

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

Ko&Tang, 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.

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

- *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,

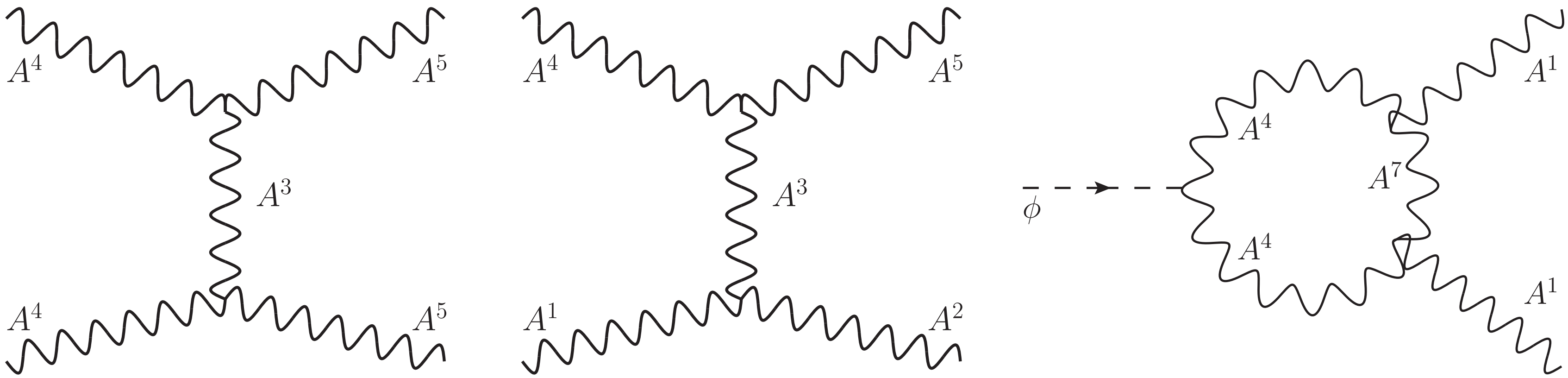
$$a \subset [1, 2, ..., (N-1)^2 - 1], a \subset [(N-1)^2, ..., N^2 - 1].$$

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

Ko&Tang, 1609.02307

- Scattering and decay processes



- 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

Chiral Dark Radiation

Ko, Nagata, Tang, 1706.05605

	S	χ_L	$\overline{\chi}_R$	Ψ_1	Ψ_2	$\overline{\Psi}_1$	$\overline{\Psi}_2$
$SU(N)$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{N}$	$\mathbf{N}$	$\overline{\mathbf{N}}$	$\overline{\mathbf{N}}$
$U(1)$	0	$+1$	-1	Q_Ψ	$-Q_\Psi$	$-(Q_\Psi - 2)$	$Q_\Psi - 2$
$U(1)_B$	0	0	0	$+1$	$+1$	-1	-1

Other context, Harigaya&Nomura, 1603.03430

- Lagrangian

$$\mathcal{L}_{\text{hid}} = \sum_{i=1,2} \Psi_i^\dagger \overline{\sigma}^\mu i\mathcal{D}_\mu \Psi_i + \sum_{i=1,2} \overline{\Psi}_i^\dagger \overline{\sigma}^\mu i\mathcal{D}_\mu \overline{\Psi}_i + \overline{\chi}\left(i\not{\mathcal{D}} - m_\chi\right)\chi + \frac{1}{2}\partial_\mu S \partial^\mu S$$
$$- \{y\overline{\chi}_R \chi_L S + \text{h.c.}\} - V_{\text{sca}} \ ,$$

$$V_{\text{sca}} = \frac{1}{2} m_S^2 S^2 + \left(\mu_{S\Phi} S + \lambda_{S\Phi} S^2\right)\Phi^\dagger \Phi + \xi_S S + \frac{\kappa_S}{3!} S^3 + \frac{\lambda_S}{4!} S^4$$

- DM χ is like dark lepton

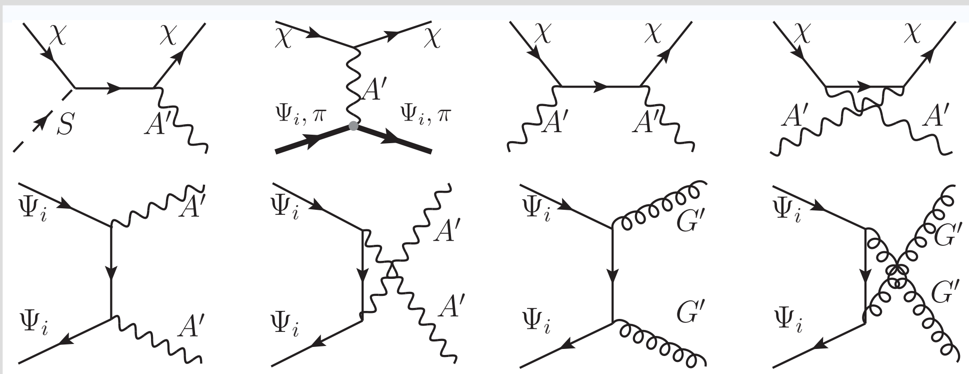
Model Features

- Chiral fermions' mass terms are forbidden by the symmetries, acting as dark radiation,
- U(1) coupling is small, ~10^{-3-4}, approximate flavour symmetry, $SU(2)_L \times SU(2)_R$
- Below SU(N) confinement($\lesssim 1\mathrm{eV}$), light dark pions arise, also massive but light dark gauge boson because the condense breaks U(1),

$$\langle\overline{\Psi}\Psi\rangle \equiv \langle\Psi_1\overline{\Psi}_1 + \Psi_1^\dagger\overline{\Psi}_1^\dagger\rangle = \langle\Psi_2\overline{\Psi}_2 + \Psi_2^\dagger\overline{\Psi}_2^\dagger\rangle \neq 0\ ,$$

  dark pion and gauge boson as dark radiation.
- Scattering between DM and DR induces diffuse damping and can suppress the matter power spectrum.

Thermal History



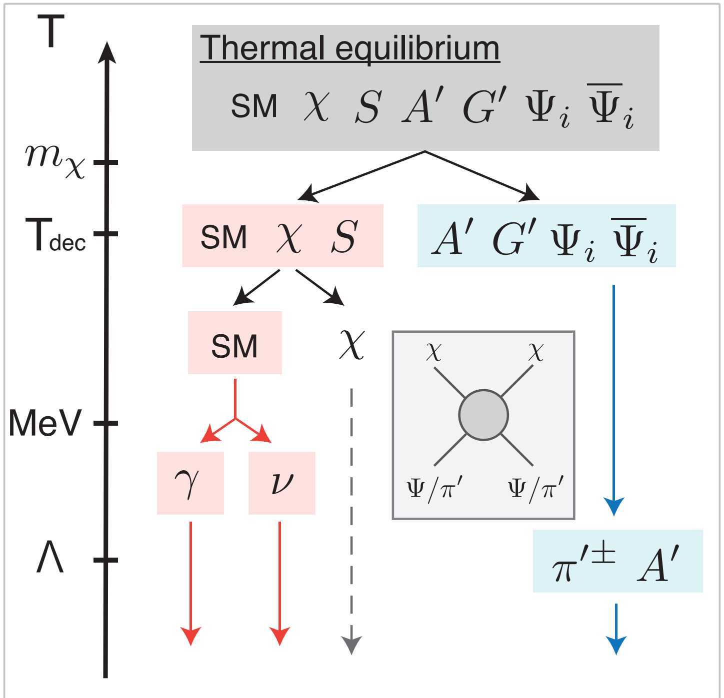


Figure 3: Thermal history of our model.

- Equilibrium at High T,
- kinetic decoupling of chiral sector,
- Chemical decoupling of DM from SM,
- DM scatters with chiral fermions/NG bosons through U(1) gauge interaction, till matter domination.
- Neff constrains the confinement scale <1eV

$$N = 2, \delta N_{\rm eff} = 0.59(0.97)$$

Other Related Work

- Partially Acoustic DM, *Chacko, Cui, Hong, Okui, and Tsai, arXiv:1609.03569*
- Partially Acoustic DM and Cosmological Constraints, *Raveri, Hu, Hoffman, Wang, arXiv:1709.04877*
- Lyman-alpha forest and DM-DR interaction, *Krall, Cyr-Racine and Dvorkin, arXiv:1705.08894*
- Interacting Dark Sector and Precision Cosmology, *Buen-Abad, Schmaltz, Lesgourgues, Brinckmann, arXiv:1708.09406*
- Dark Catalysis, *Agrawal, Cyr-Racine, Randall, Scholtz, arXiv:1702.05482*
- *……*

Summary

- We discussed possible cosmological effects in some *interacting* Dark Matter models with Dark Radiation
- Such scenarios are motivated theoretically and also from observational tensions, ex: H_0 and σ_8
- It might be possible to resolve two tensions by modifying the DM sector
- We present several particle physics models:
  - A massless dark photon with *unbroken gauged U(1)*
  - *Residual non-Abelian* DM and DR
  - Hidden charged DM with chiral fermions

Thanks for your attention.