Small (and large) scale structure beyond SIDM

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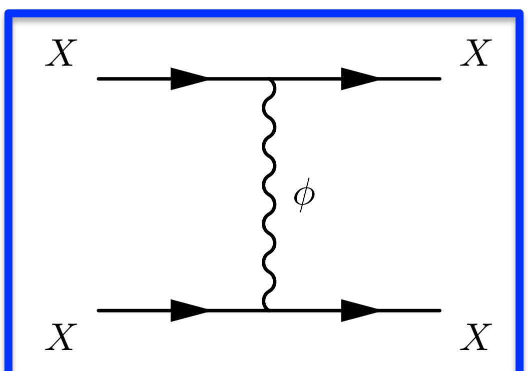
Beyond SIDM: Motivation

	Missing satellites	Cusp vs. core	Too big to fail
Baryons	✓	✓	✓
SIDM	✗	✓	✓



Cherry et al., (2014)

Beyond SIDM: Motivation

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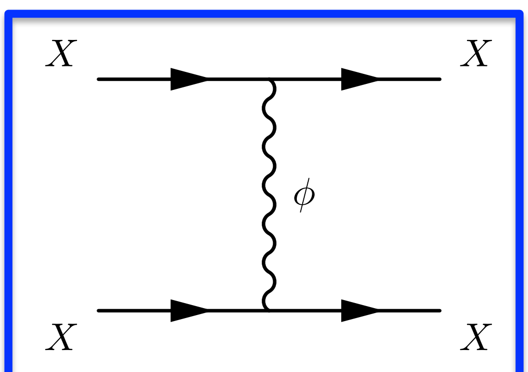
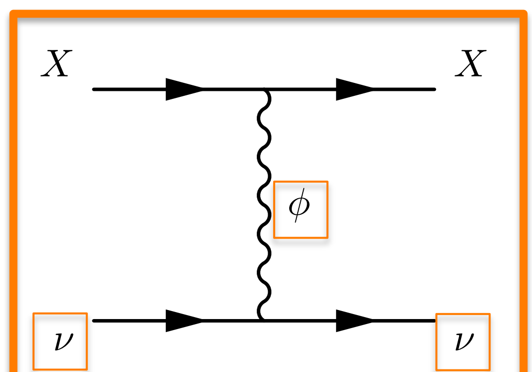
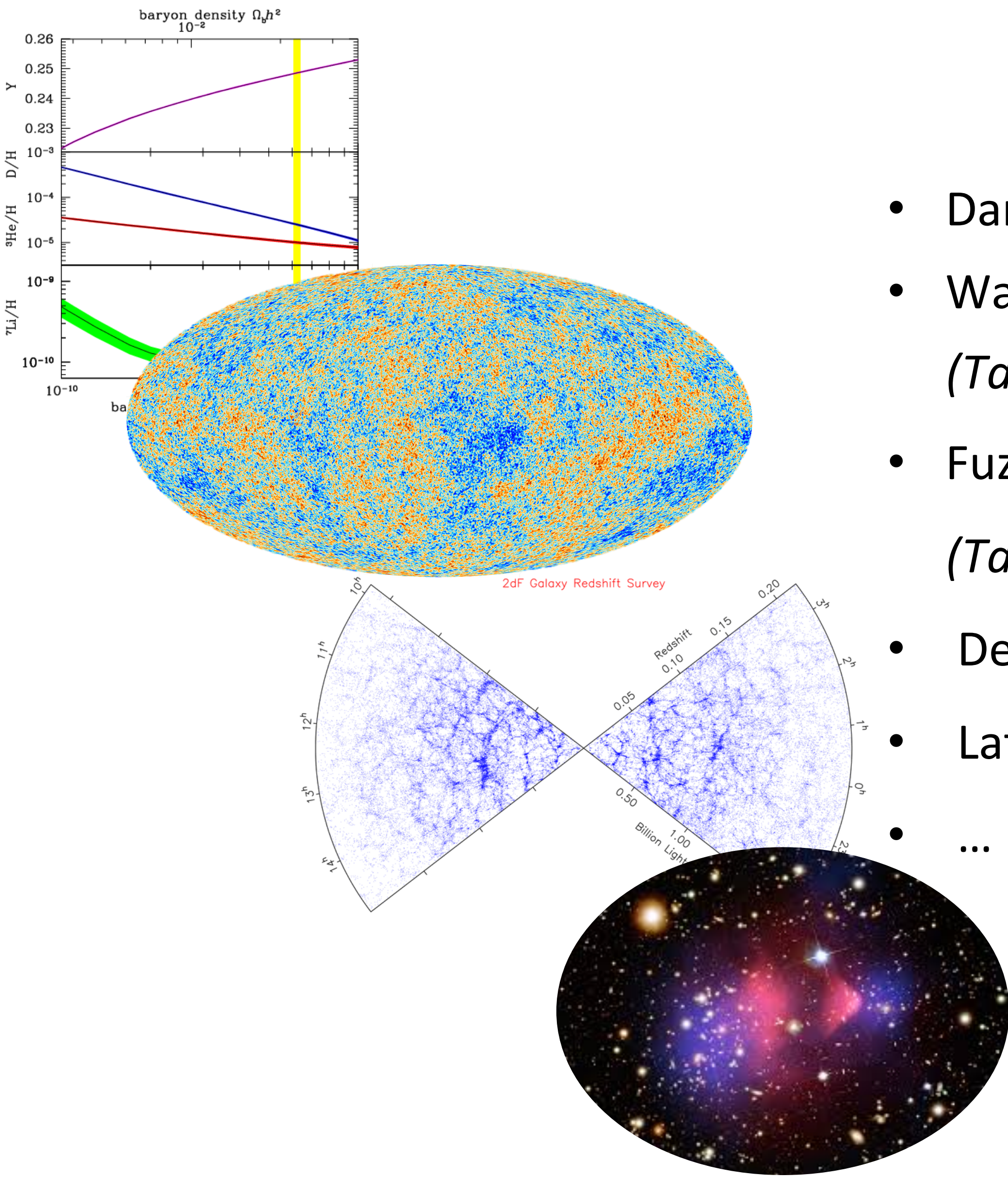
Baryons	✓	✓	✓
SIDM	✗	✓	✓
SIDM + DR	✓	✓	✓





Cherry et al., (2014)

Beyond SIDM: small (and large) scales

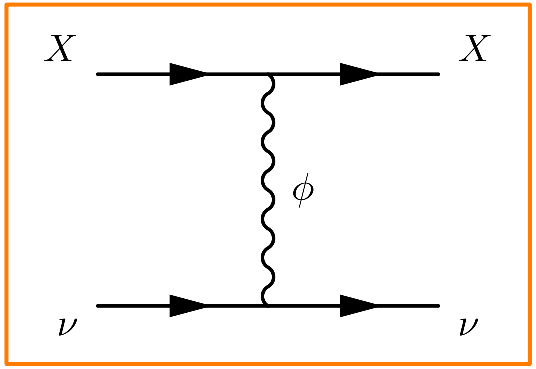


- Dark Radiation – Dark Matter
- Warm Dark Matter

  (Talk by Laura Lopez-Honorez)
- Fuzzy Dark Matter

  (Talk by Luca Visinelli)
- Decaying Dark Matter
- Late Forming Dark Matter
- …

Dark radiation - dark matter interactions



Timeline

Temperature	Process	Probe
$T_\chi \sim m_\chi / 25$	DM freeze-out	DM relic abundance
T > 200 MeV	Dark sector decoupling	N_{eff} BBN & CMB
$T_\gamma \sim 1$ MeV	BBN & ν decoupling	
$T_{Dark} > 100$ eV	DM kinetic decoupling*	CMB, Ly-α, Astrophys. obs.
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Structure formation	DM self-interactions	Astrophysical observations

*= since $H \sim T^2$ during RDE, there is decoupling only if $\tau^{-1} \sim T^n$ with n>2, otherwise dark matter and dark radiation recouple at later times.

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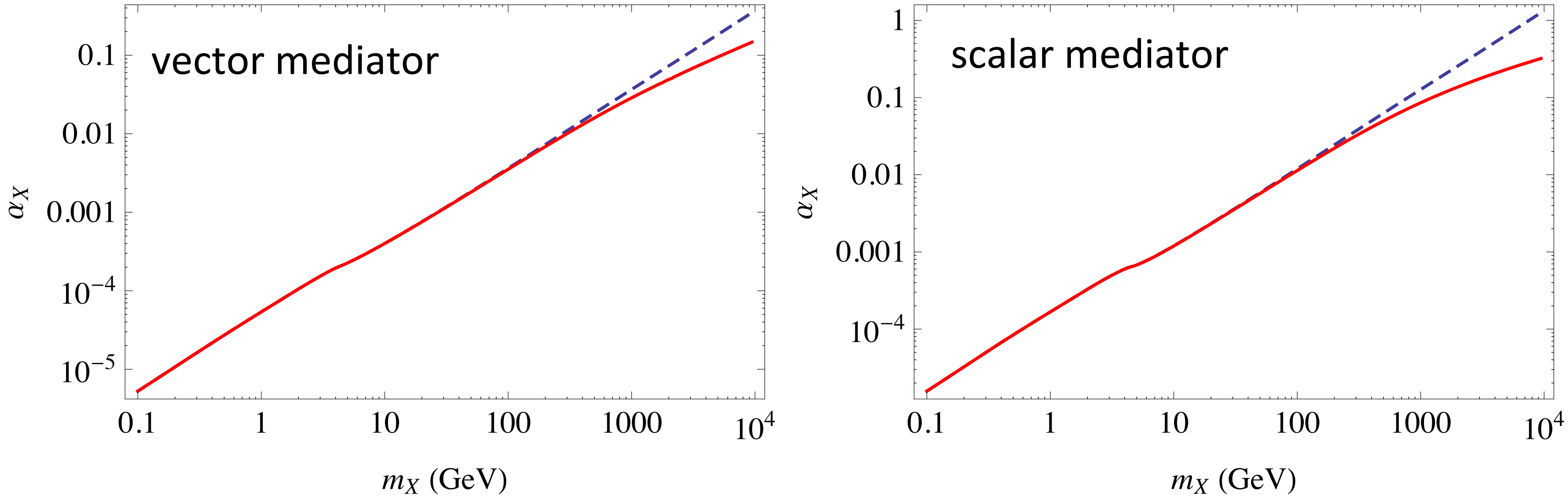
Dark matter: bounds from the relic abundance

$\chi\bar{\chi} \to \phi\phi$ dominates over $\chi\bar{\chi} \to \nu\nu$ if $g_\chi^2 > \frac{N_\nu}{2} g_\nu^2$

$$\Omega_\chi h^2 \propto x_f \frac{\sqrt{g_*}}{g_{*S}} \frac{m_\chi^2}{g_\chi^4}$$

Sommerfeld enhancement



Tulin et al., PRD (2013)

Timeline

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Dark radiation

$$\boxed{\xi(T) = \frac{T_{dark}}{T_{(\gamma)}}}$$

$$g_{*S}(T) = g_{*S,vis}(T) + \sum_{i=bosons} g_{dark}(T)\xi^3(T) + \frac{7}{8}\sum_{i=fermions} g_{dark}(T)\xi^3(T)$$

$$s_{tot}(T) \propto g_{*S}(T)T^3$$

$$\xi^3(T_{BBN}) = \xi^3(T_{RH})\frac{g_{*S,vis}(T_{BBN})}{g_{*S,vis}(T_{RH})}\frac{g_{dark}(T_{RH})}{g_{dark}(T_{BBN})}; \;\; \xi(T_{RH}) = 1$$

$$\xi^3(T_{CMB}) = \xi^3(T_{BBN})\left(\frac{4}{11}\right)$$

For massless dark radiation and massive mediator

$$\rho_{rad} \propto g_* T^4$$

$$\Delta N_{eff}(T_{BBN/CMB}) = \frac{\left(\sum_{i=bosons} g_{dark}(T) + \frac{7}{8}\sum_{i=fermions} g_{dark}(T)\right)}{2\times 7/8}\frac{\xi^4(T_{BBN/CMB})}{(4/11)^{4/3}}$$

Equivalent neutrino number

$$\rho_{rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_\gamma, \qquad N_{eff} = 3.046 + \Delta N_{eff}$$

Dark radiation: constraints from BBN

Shortly after neutrino decoupling the weak interactions that kept neutrons and protons in statistical equilibrium freeze out.

$$H = \Gamma\big|_{T=T_{freeze}} \qquad T_{freeze} \approx 0.6 g_*^{1/6}\ MeV$$

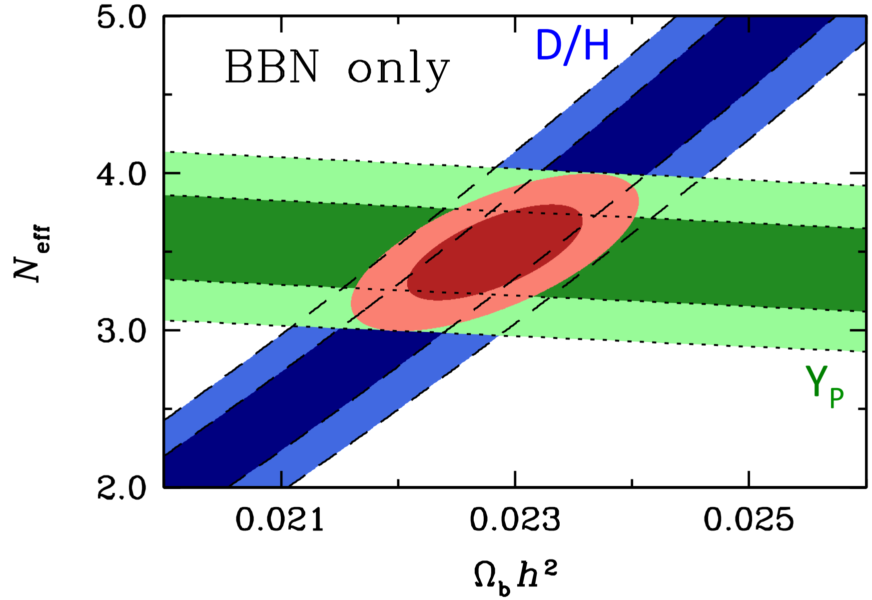
$$\left.\frac{n_n}{n_p}\right|_{T=T_{freeze}} \approx \exp\left(-\frac{(m_n - m_p)}{T_{freeze}}\right) \approx \frac{1}{6}$$

$$Y_P \approx \left.\frac{2n_n/n_p}{1+n_n/n_p}\right|_{T\approx 0.2\,MeV} \propto f(g_*, \Omega_b h^2)$$

$$g_* \longrightarrow g_* + \frac{7}{4}\Delta N_{eff}$$

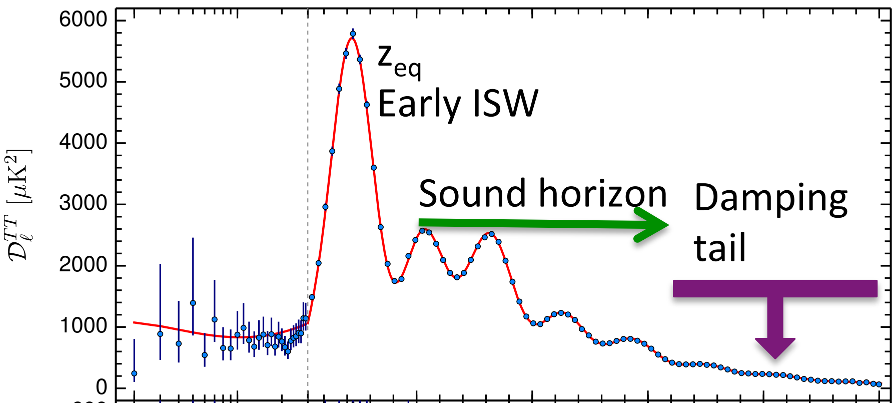
$$\left|Y_P^{theo} - Y_P^{obs}\right|_{\Omega_b} \longrightarrow \Delta N_{eff}\big|_{\Omega_b}$$

Cooke et al., MNRAS (2013)



$$\boxed{\Delta N_{eff}(BBN) < 1\ \ (95\% c.l.)}$$

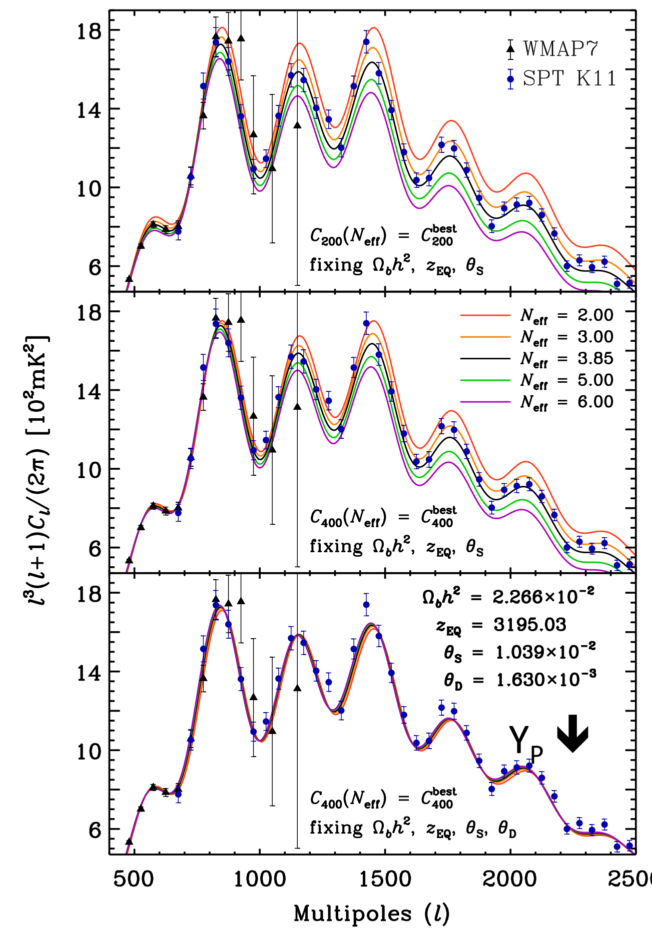
Dark radiation: constraints from CMB



$$r_s = \int_0^{a_*} \frac{c_s}{a^2}\frac{da}{H}$$

$$\theta_d = \frac{r_d}{D_A} \propto \frac{H^{-0.5}}{H^{-1}}$$

Hou et al., PRD (2013)



Background effects:

- expansion rate

Perturbation effects (free-streaming):

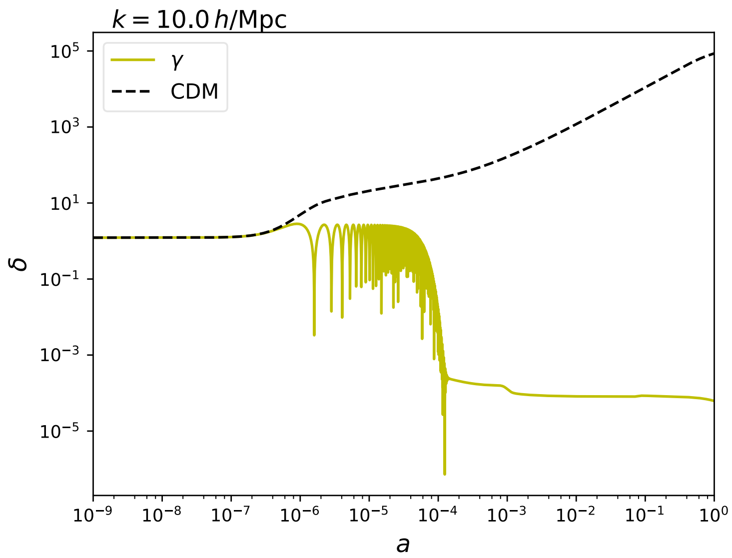
- phase shift in δ_γ
- overall amplitude suppression (anisotropic stress)

$$\boxed{N_{eff}(CMB) = 2.99 \pm 0.20 \ \ (68\%cl) \rightarrow \xi \leq 0.5 \ \ (95\%cl)}$$

The signature of dark matter-dark radiation on the CMB

The clustering of cold dark matter before baryon drag is described by the Meszaros equation: $\ddot{\delta}_c^{slow} + \frac{\dot{a}}{a}\dot{\delta}_c^{slow} = 4\pi G a^2 \rho_c \delta_c^{slow}$ CDM is self-gravitating

For photons: $(1+R)\ddot{\delta}_\gamma^{fast} + \frac{\dot{a}}{a}\dot{\delta}_\gamma^{fast} + \frac{1}{3}k^2 R \delta_\gamma^{fast} = 0$ ➔ CMB primary anisotropies



$$\dot{\delta}_{DM} + \theta_{DM} - 3\dot{\phi} = 0$$

$$\dot{\theta}_{DM} - k^2 c_D^2 \delta_{DM} + H\theta_{DM} - k^2\psi = 0$$

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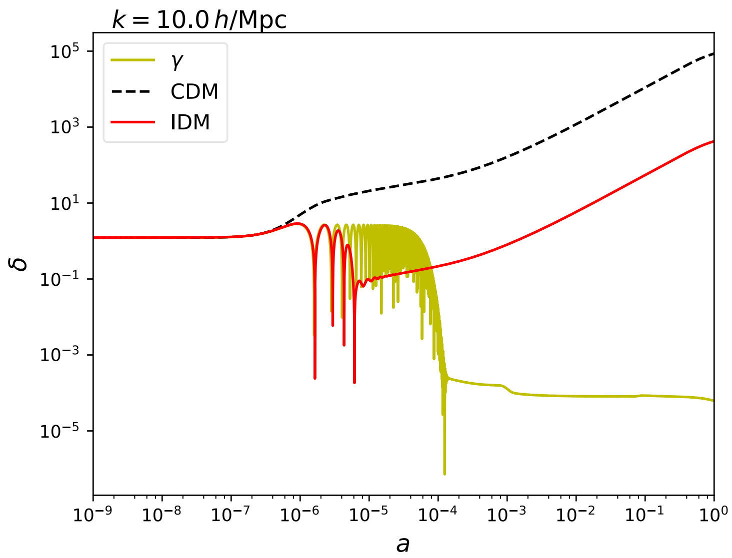

$$\dot{\delta}_{DM} + \theta_{DM} - 3\dot{\phi} = 0$$
$$\dot{\theta}_{DM} - k^2 c_D^2 \delta_{DM} + H\theta_{DM} - k^2\psi = \Gamma_{DM}(\theta_{DM} - \theta_{DR})$$

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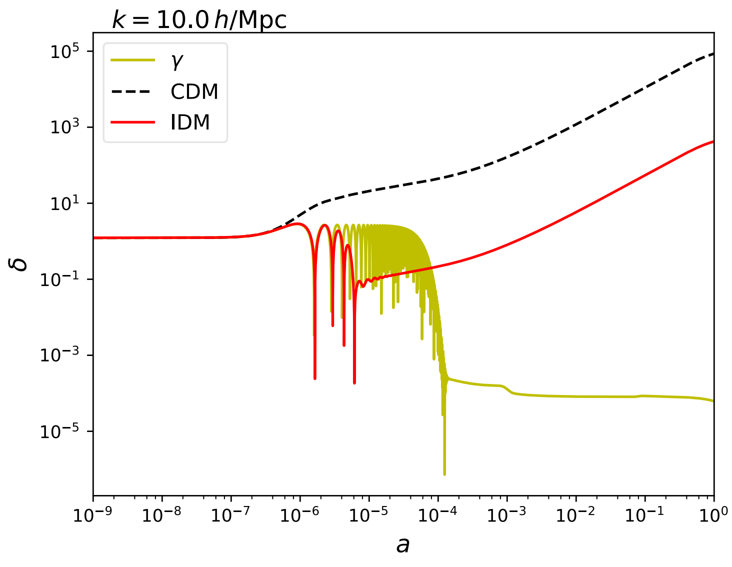
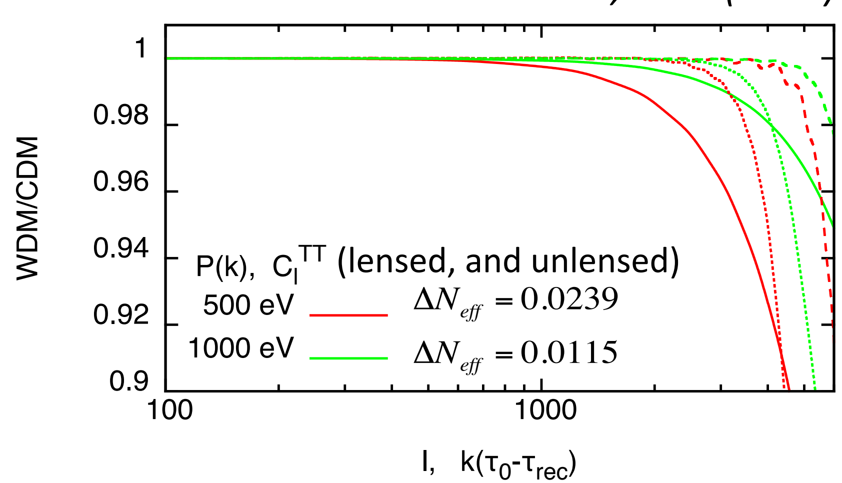


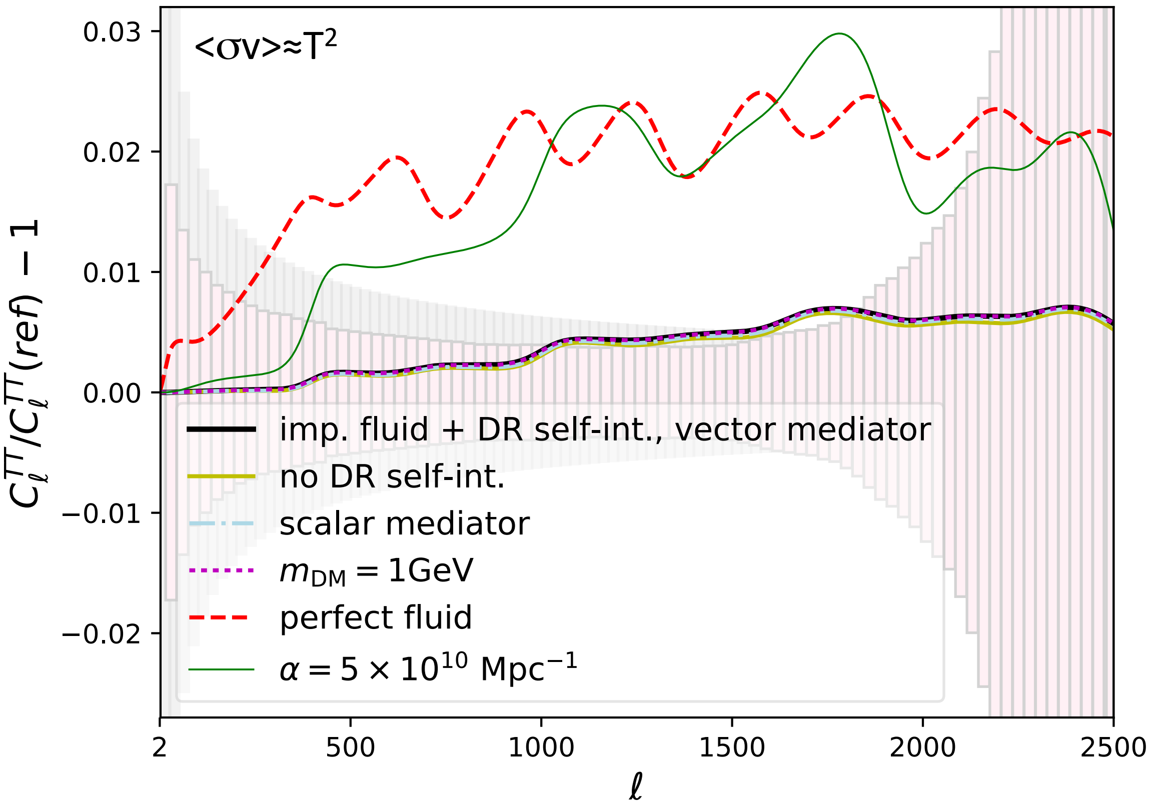
WDM: fast modes before nr transition
slow modes after

Voruz et al., JCAP (2014)



The signature of dark matter-dark radiation on the CMB

Archidiacono et al., (2017)



Relative change wrt ΛCDM+ΔN_{eff} (same bkg.)

- Scale dependent phase shift and amplitude suppression

If during MDE DM is still coupled: relative suppression of the odd (compression) peaks.

See also:

Atomic DM

Cyr-Racine et al., PRD (2013)

Cyr-Racine et al., PRD (2014)

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Kinetic decoupling: bounds from Ly-α

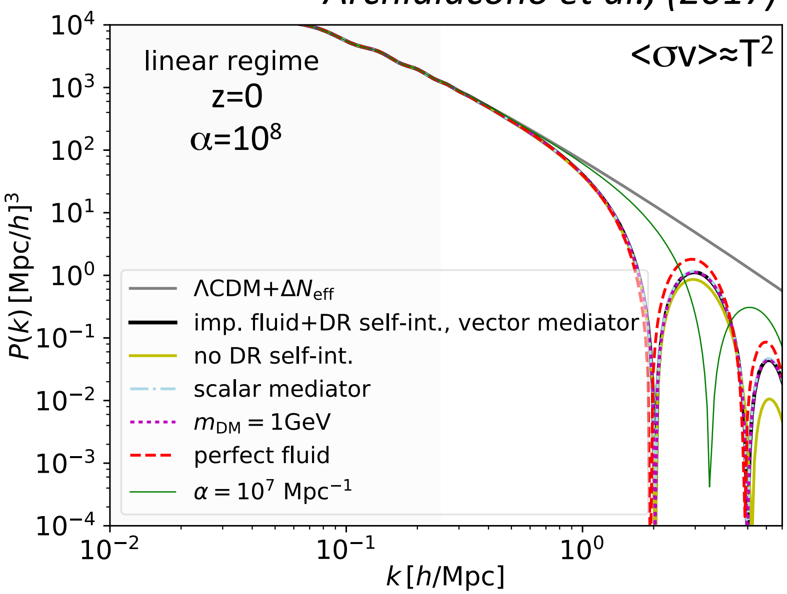
Talk by T. Binder

$$\Gamma_{DM} = H \rightarrow T_{kd}(m_\chi, m_\phi, g_\chi, g_\nu, \xi)$$

The mass of the smallest proto-halos corresponds to the mass enclosed in the Hubble horizon at the time of kinetic decoupling.

$$M_{cut} = \frac{4\pi}{3}\rho_m\left(\frac{1}{H}\right)^3 \approx 2\times10^8\left(\frac{keV}{T_{kd}}\right)^3 M_{Sun}$$

Archidiacono et al., (2017)

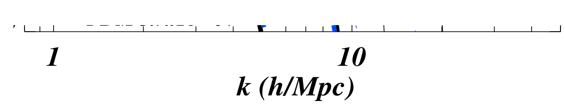


$$M(k) \approx 10^{12}\left(\frac{Mpc^{-1}}{k}\right)^3 M_{Sun}$$

- Non-linear regime
- Ly-α *Irsic et al., (2017)*

→ HIRES/MIKE

→ XQ-100

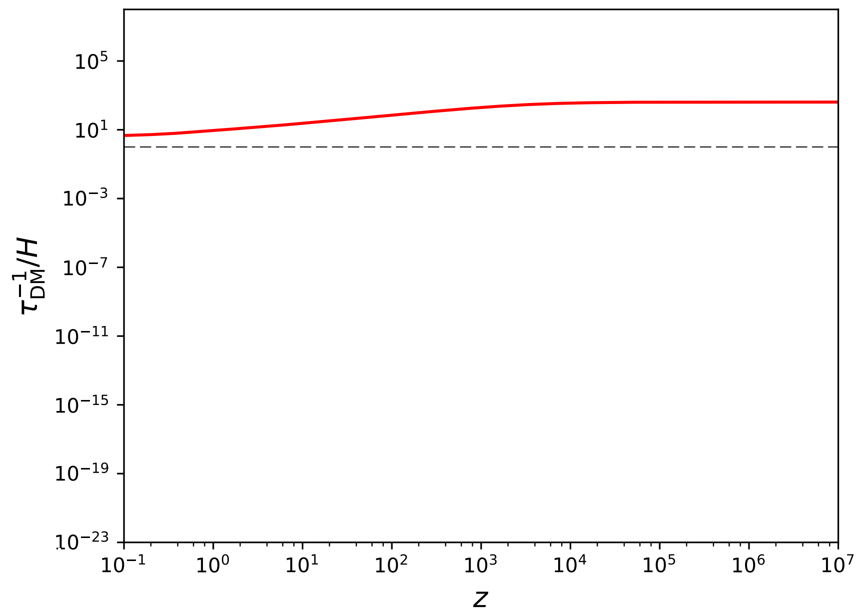


Models on the market

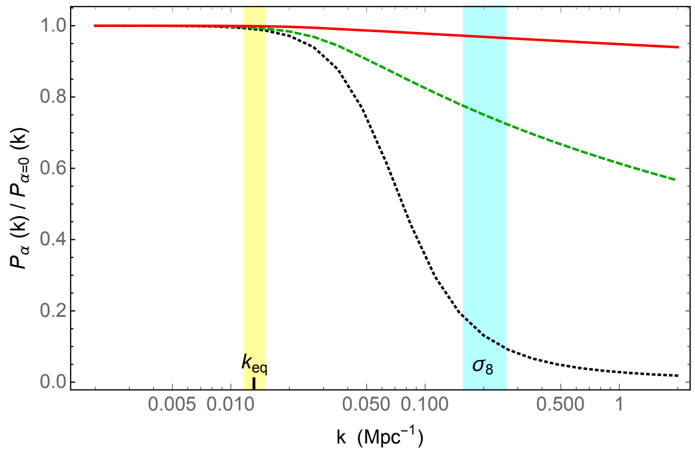
Models on the market

- $\tau_{DM}{}^{-1} \sim T^2$ Non-Abelian DM

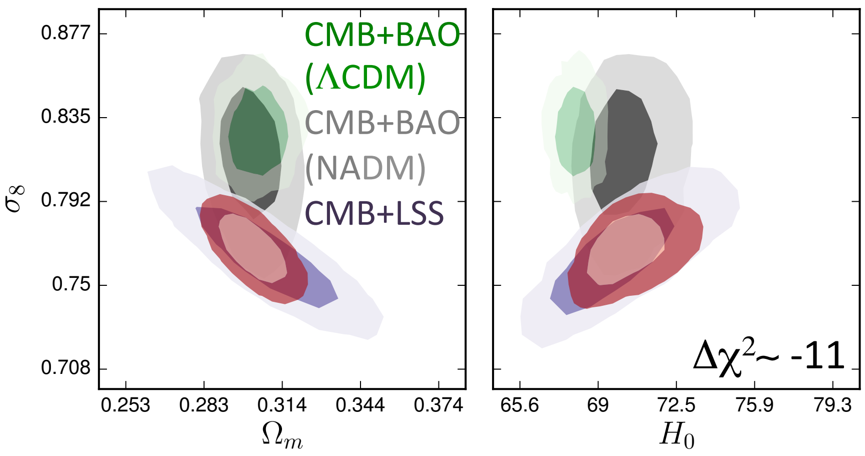
Buen-Abad et al., PRD (2015)



Talk by F.Y. Cyr-Racine



Lesgourgues et al., JCAP (2016)



$\Delta\chi^2 \sim$ -6
Krall et al., (2017)

Models on the market

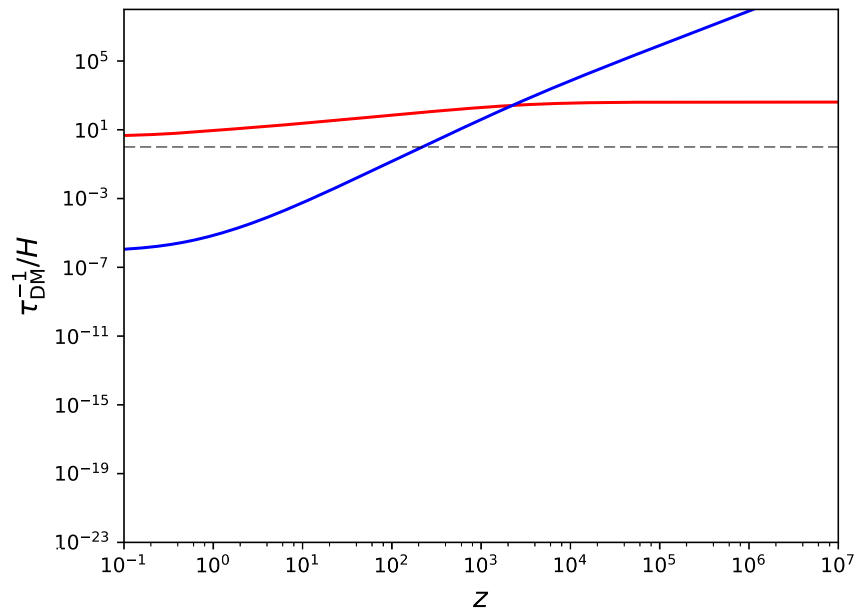
- $\tau_{DM}^{-1} \sim T^2$ Non-Abelian DM

  Buen-Abad et al., PRD (2015)

- $\tau_{DM}^{-1} \sim T^4$ ~massless mediator

  const. cross section

  Wilkinson et al., JCAP (2014)

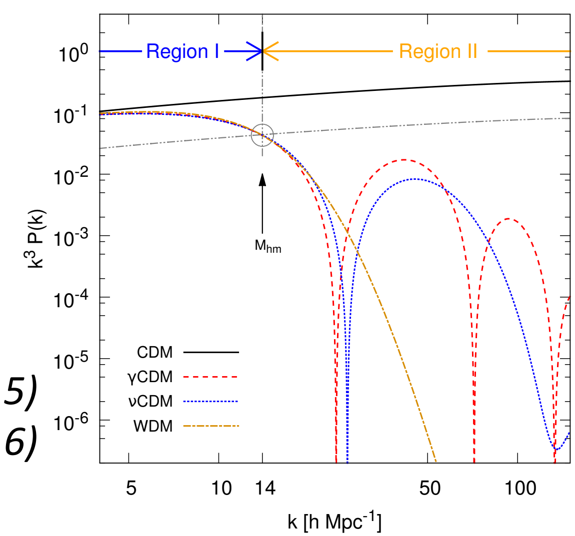


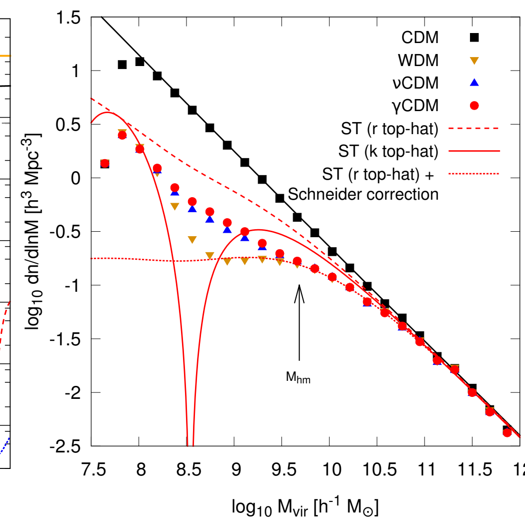
Lyman-α:

$$\sigma_{\nu-DM} \leq 10^{-33} (m_{DM} / GeV) cm^2$$

(no effect on CMB)

Boehm et al., MNRAS (2014)
Schewtschenko et al., MNRAS (2015)
Schewtschenko et al., MNRAS (2016)





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  const. cross section
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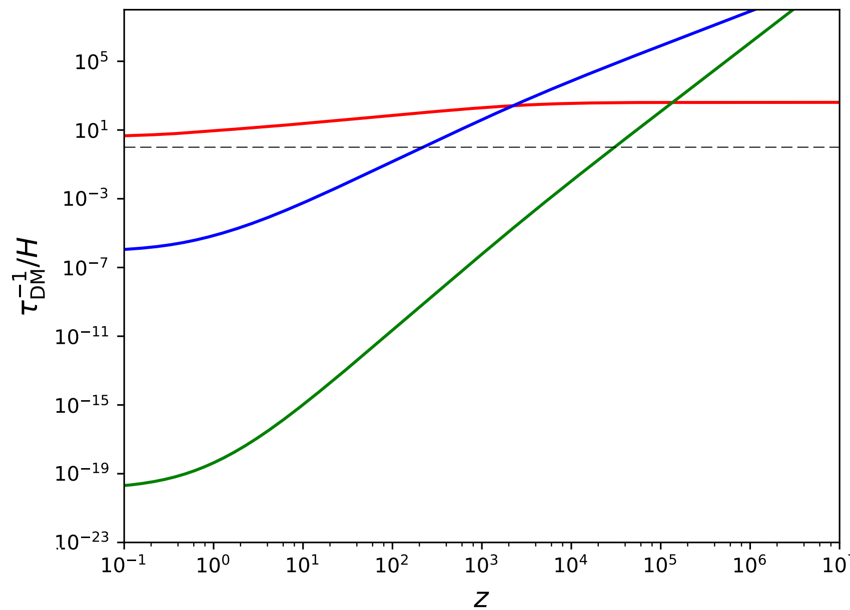
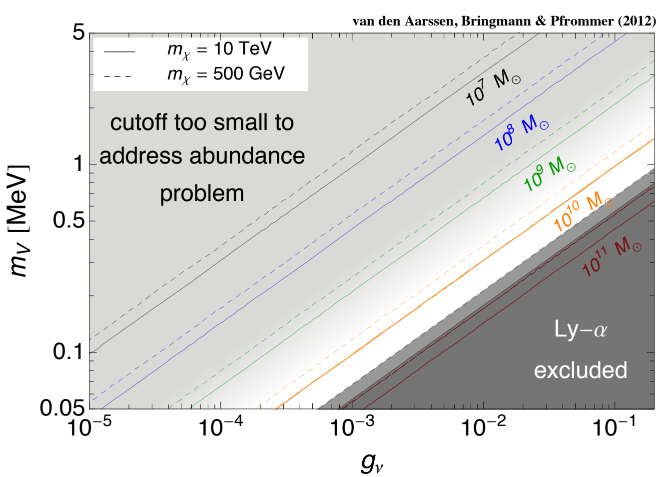
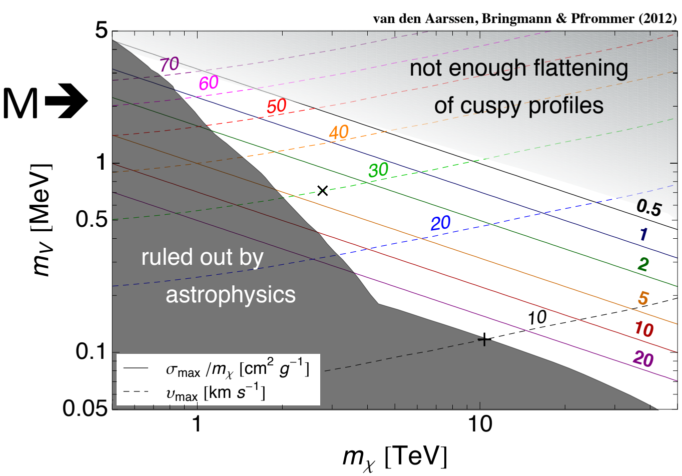
- $\tau_{DM}^{-1} \sim T^6$ massive mediator
  Van den Aarssen et al., PRL (2012)





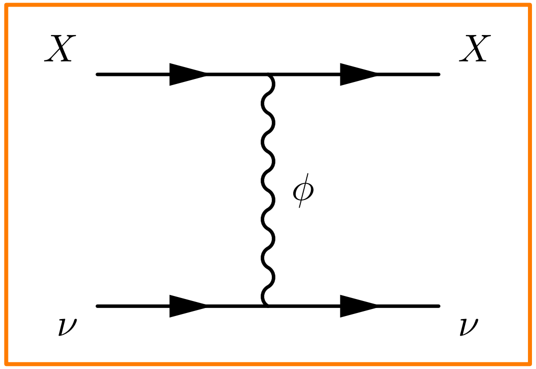
← DM-DR

SIDM →

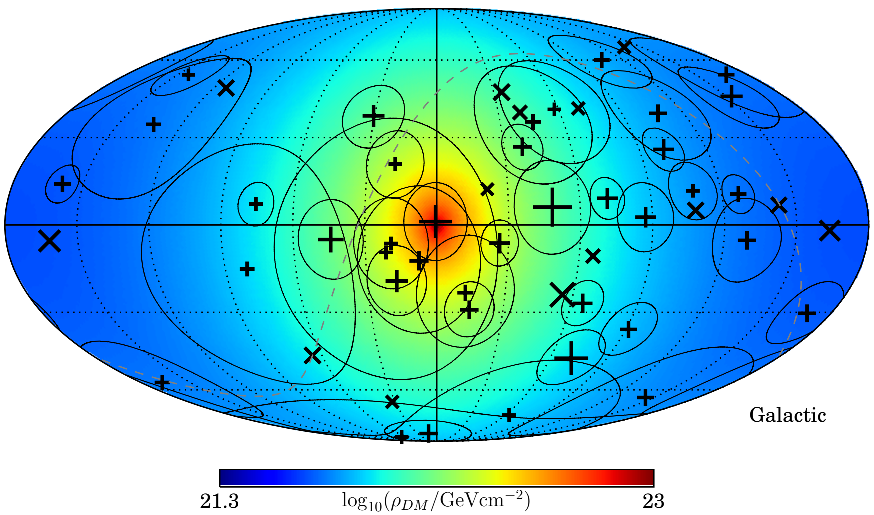


See also:
Vogelsberger et al., MNRAS (2016)

Coupling to active neutrinos

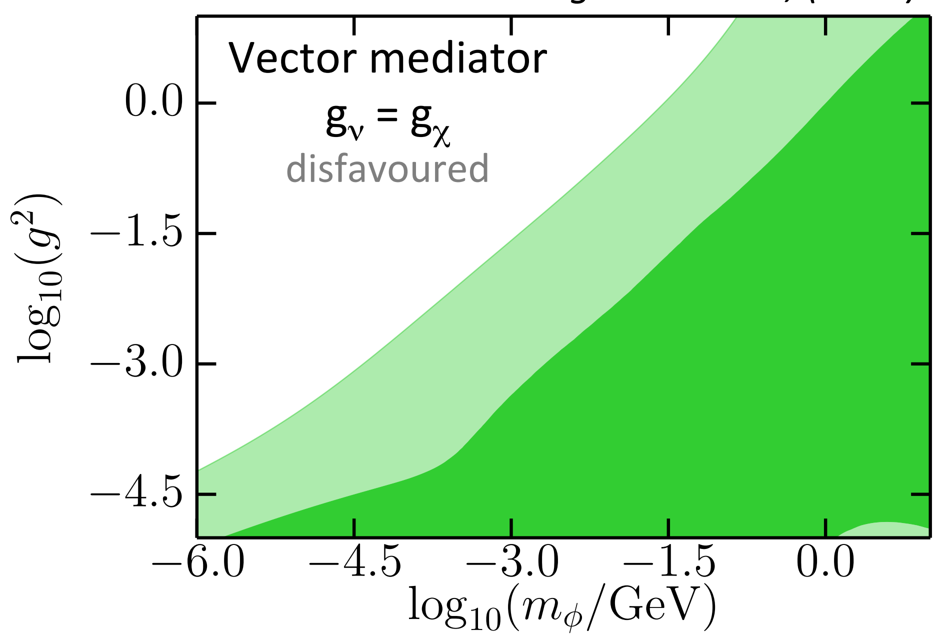


Constraints on DM-ν

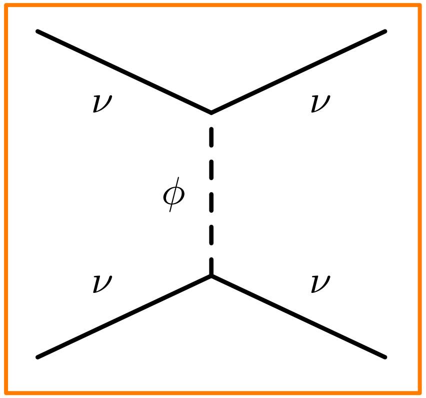


Constraints on DM-neutrino interactions from the extragalactic signal of high energy neutrinos (IceCube).

Arguelles et al., (2017)



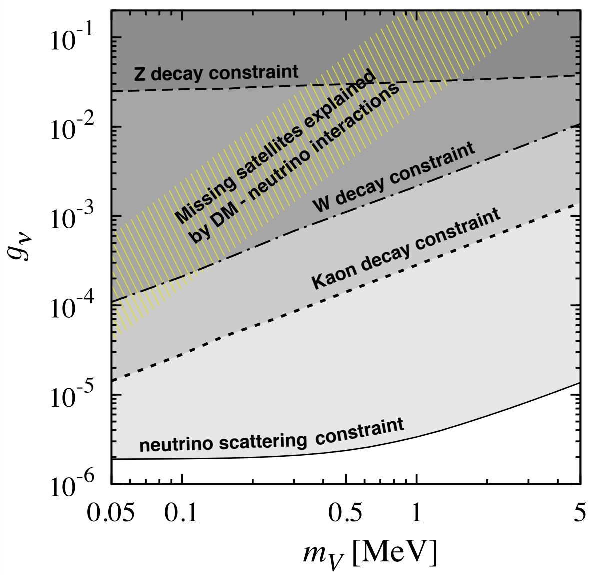
Active neutrino self-interactions



Constraints on active νSI

Constraints from the lab.

Laha et al., PRD (2014)



Z, W, and kaon decays, and electron neutrino scattering.

Astrophysical constraints

Kolb & Turner, PRD (1987)

Supernova 1987A and the secret interactions of neutrinos

Edward W. Kolb
Osservatorio Astronomico di Roma, via del Parco Mellini 84, 00136 Rome, Italy
and NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510
and Department of Astronomy and Astrophysics, The University of Chicago, Chicago, Illinois 60637

Michael S. Turner
NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510
and Department of Astronomy and Astrophysics, The University of Chicago, Chicago, Illinois 60637
and Department of Physics and the Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637

(Received 13 July 1987)

By using SN1987A as a "source" of neutrinos with energy ~ 10 MeV we place limits on the couplings of neutrinos with cosmic background particles. Specifically, we find that the Majoron–electron-neutrino coupling must be less than about 10^{-3}; if neutrinos couple to a massless vector particle, its dimensionless coupling must be less than about 10^{-3}; and if neutrinos couple with strength g to a massive boson of mass M, then g/M must be less than 12 MeV^{-1}.

Massive mediator: $g/M < 12\ \text{MeV}^{-1}$

Constraints on active νSI

Cosmological constraints CMB

$$\dot{\Psi}_0 = -k\frac{q}{\varepsilon}\Psi_1 + \frac{1}{6}\dot{h}\frac{d\ln f_0}{d\ln q}$$

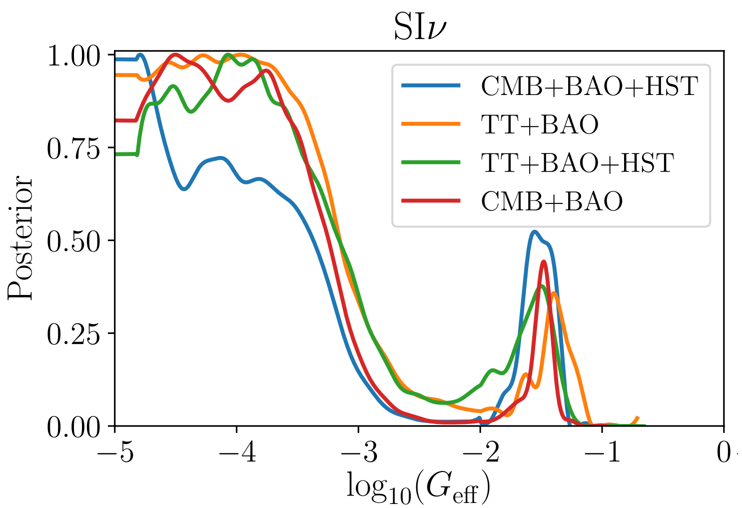
$$\dot{\Psi}_1 = k\frac{q}{3\varepsilon}(\Psi_0 - 2\Psi_2)$$

$$\dot{\Psi}_2 = k\frac{q}{5\varepsilon}(2\Psi_1 - 3\Psi_3) - \left(\frac{1}{15}\dot{h} + \frac{2}{5}\dot{\eta}\right)\frac{d\ln f_0}{d\ln q} - a\tau_\nu^{-1}\Psi_2$$

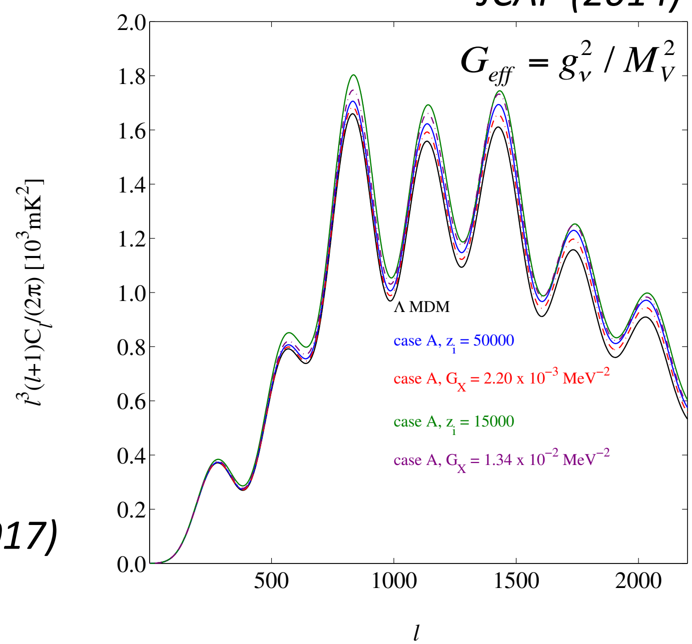
$$\dot{\Psi}_l = k\frac{q}{(2l+1)\varepsilon}(l\Psi_{l-1} - (l+1)\Psi_{l+1}) - a\tau_\nu^{-1}\Psi_l,\ l \geq 3$$

Archidiacono, Hannestad, JCAP (2014)

Oldengott et al., (2017)



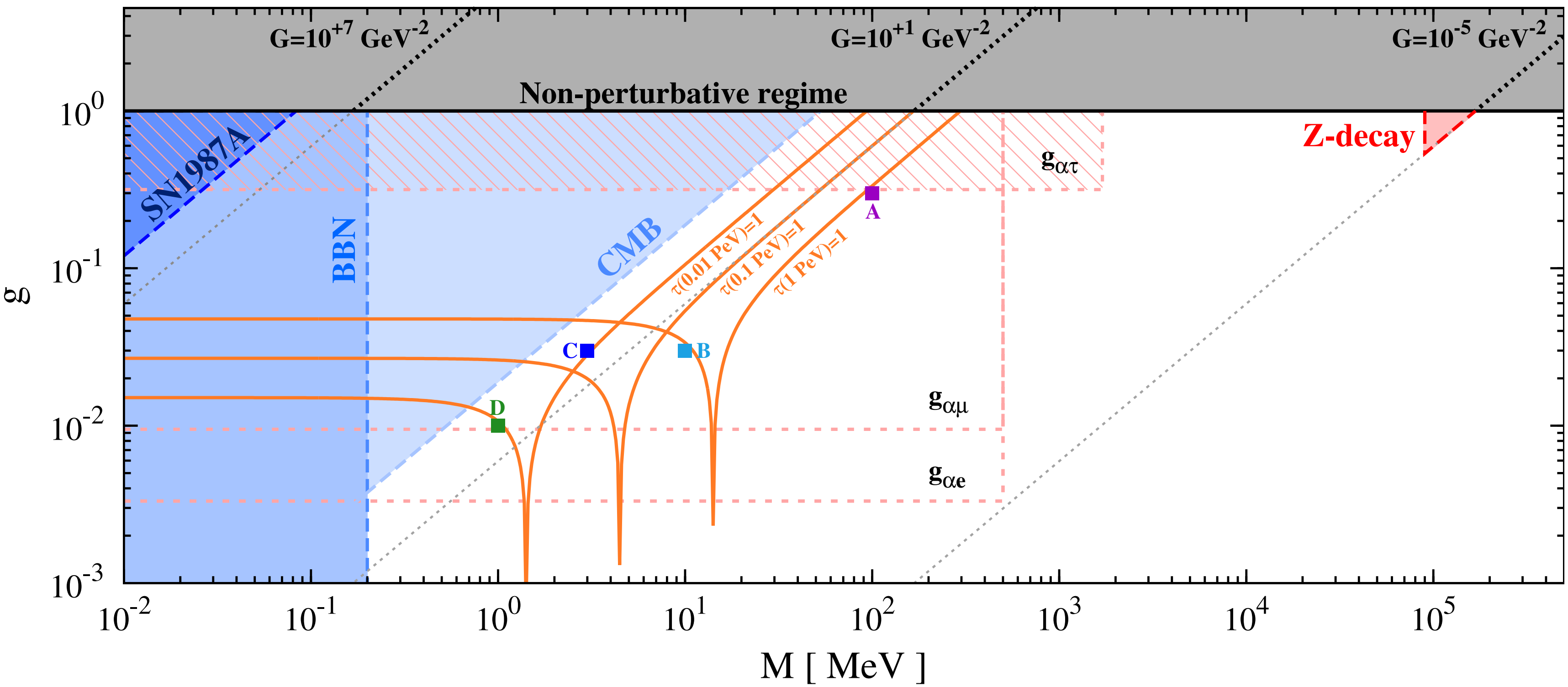
See also: Brust et al., (2017)



Constraints on active νSI summary

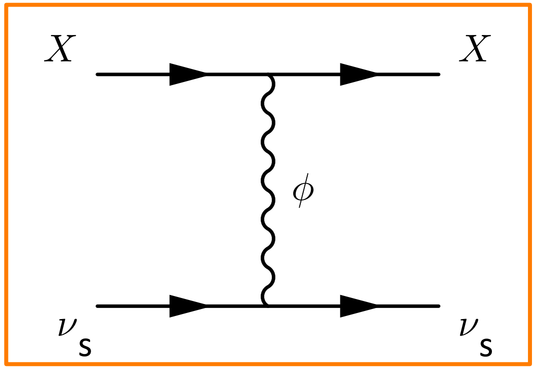
Massive scalar mediator

Ng & Beacom, PRD (2014)



Dark matter coupling to active neutrinos is strongly constrained.

Coupling to (eV) sterile neutrinos



Talk by J. Kersten

The case for sterile neutrinos

BBN: $N_{eff} < 4$ (95%c.l.)

(Planck + LSS)

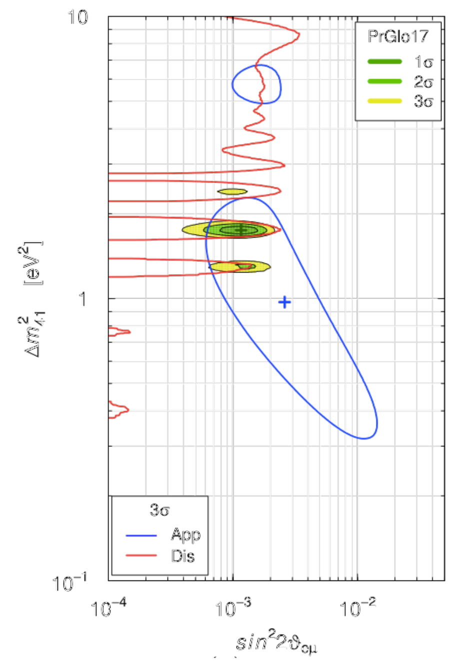
ΛCDM + Σm_ν
$\Sigma m_\nu < 0.2$ eV (95%c.l.)

ΛCDM + N_{eff}
$N_{eff} = 3.15 \pm 0.23$ (68%c.l.)

ΛCDM + N_{eff} + $m^{eff}_{\nu,\,sterile}$
$N_{eff} < 3.7$ & $m^{eff}_{\nu,\,sterile} < 0.38$ eV (95%c.l.)

Gariazzo et al., Global fit (2017)

$N_{eff} = 4.0\ldots$
$M_\nu \approx 1$ eV



Non-standard physics:
partial thermalization of sterile neutrinos in the early Universe.

$$\Delta N_{eff} = \frac{\rho_{\nu,s}}{\rho^{thermal}_{\nu,m=0}} \left(\frac{P_{\nu,s} / \rho_{\nu,s}}{1/3} \right); \qquad \rho = \frac{g}{2\pi^2} \int dp E p^2 f(p)$$

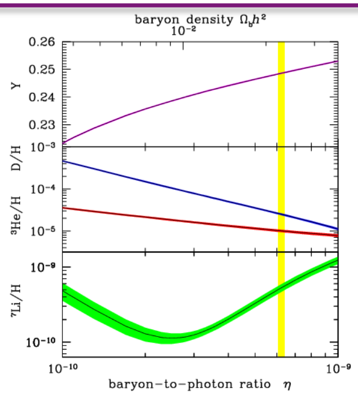
- Lepton asymmetry *Mirizzi et al., PRD (2012); Hannestad et al., JCAP (2012)*
- Low reheating scenarios *Lattanzi et al., PRD (2015)*
- "Secret" sterile neutrino self-interactions

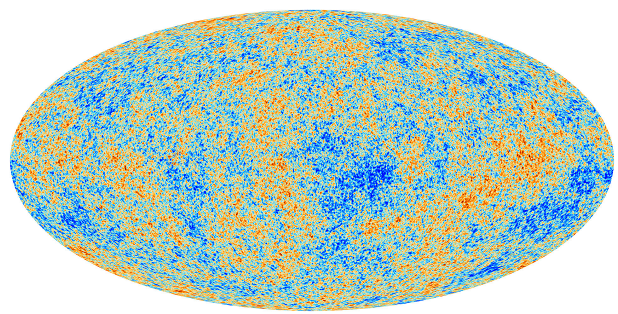
ν_s Secret Interactions

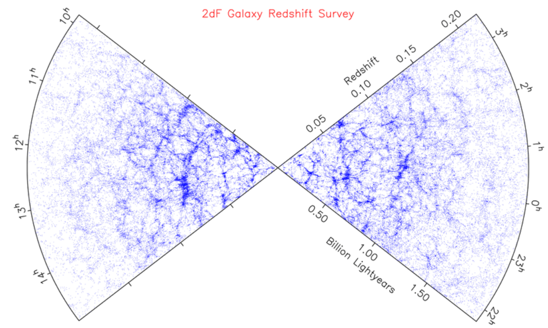
The sterile neutrino is coupled to a new light pseudoscalar (Majoron models)

$$L_{\mathrm{int}} \sim g_s \phi \bar{\nu}_s \gamma_5 \nu_s$$

The phenomenological success of the model requires:







N_{eff} & flavour

N_{eff} & (Σm_ν)

(N_{eff}) & Σm_ν

$10^{-6} < g_s < 10^{-5}$

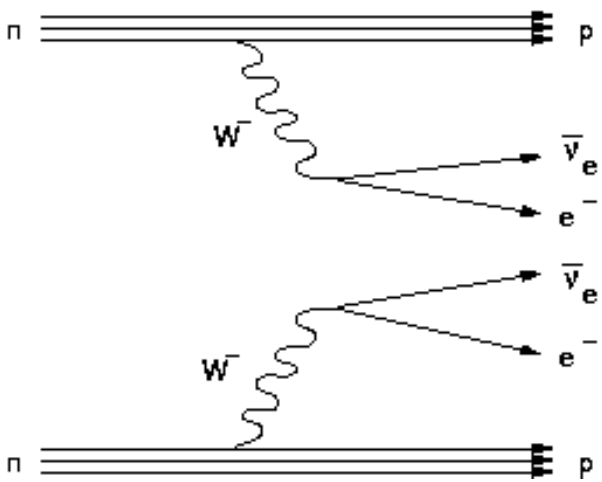
$m_\phi < 0.1\mathrm{eV}$

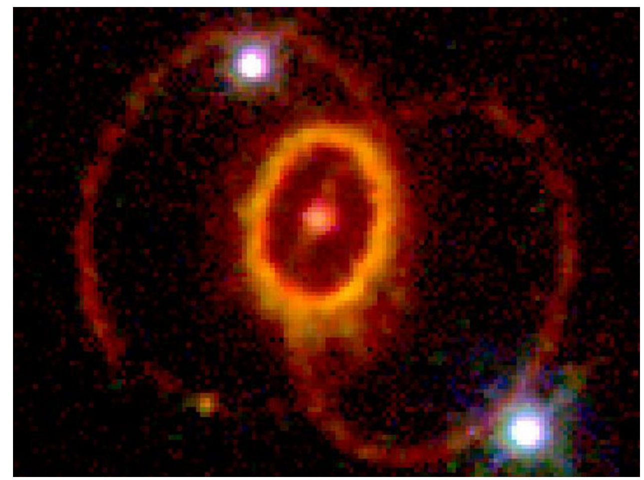
ν_s Secret Interactions

The sterile neutrino is coupled to a new light pseudoscalar (Majoron models)

$$L_{\text{int}} \sim g_s \phi \bar{\nu}_s \gamma_5 \nu_s$$

Non-cosmological constraints:





$\beta\beta$ $g_e < 3 \times 10^{-5}$

Bernatowicz et al, PRL (1992)

SN energy loss $g_e < 4 \times 10^{-7}$
$g_s < 10^{-5}$

Farzan, PRD (2003)

Early Universe: flavour evolution

Stodolsky, PRD (1987)

$$\rho(p,t)=\begin{pmatrix}\rho_{aa} & \rho_{as}\\ \rho_{sa} & \rho_{ss}\end{pmatrix}=\frac{f_0(p)}{2}\left[P_0(p,t)+\bar{\sigma}\times\bar{P}(p,t)\right];$$

$$\frac{d\bar{P}}{dt}=\bar{V}\times\bar{P}-D\bar{P}_T+\frac{R}{f_0}\hat{z}$$

$$\bar{V}=\bar{V}_{vacuum}+\bar{V}_{medium}+\bar{V}_s$$

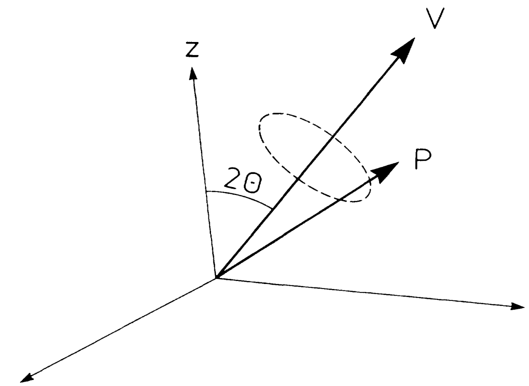
$$V_{vaccum}=\frac{\Delta m^2}{2p}$$

$$V_{medium}\propto\frac{G_F}{M_z^2}n_a pT^4$$

$D=\frac{1}{2}\Gamma$ damping

$R=\Gamma\left(f_0-\frac{f_0}{2}(P_0+P_z)\right)$ repopulation

$$\Gamma_a\propto G_F^2 pT^4$$



$$V_s(p_s)=\frac{g_s^2}{8\pi^2 p_s}\int p\,dp(f_\phi+f_s)\sim 10^{-1}g_s^2T_s$$

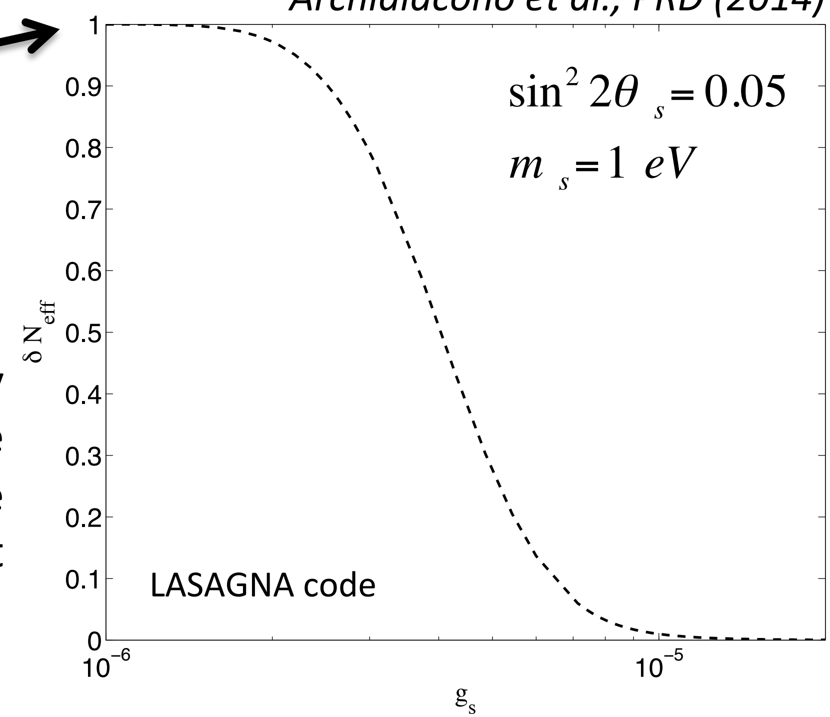
$$\Gamma_s=\frac{g_s^4}{4\pi T_s^2}n_s$$

$V_s>V_{vacuum}$ until $\frac{\Gamma_a}{H}>1$ (≈1MeV)

N_{eff} at BBN

BBN bounds:
$\Delta N_{eff} \leq 1$ (95% c.l.)

Archidiacono et al., PRD (2014)



When sterile neutrinos are produced, they will create non-thermal distortions in the sterile neutrino distribution, and the sterile neutrino spectrum end up being somewhat non-thermal.

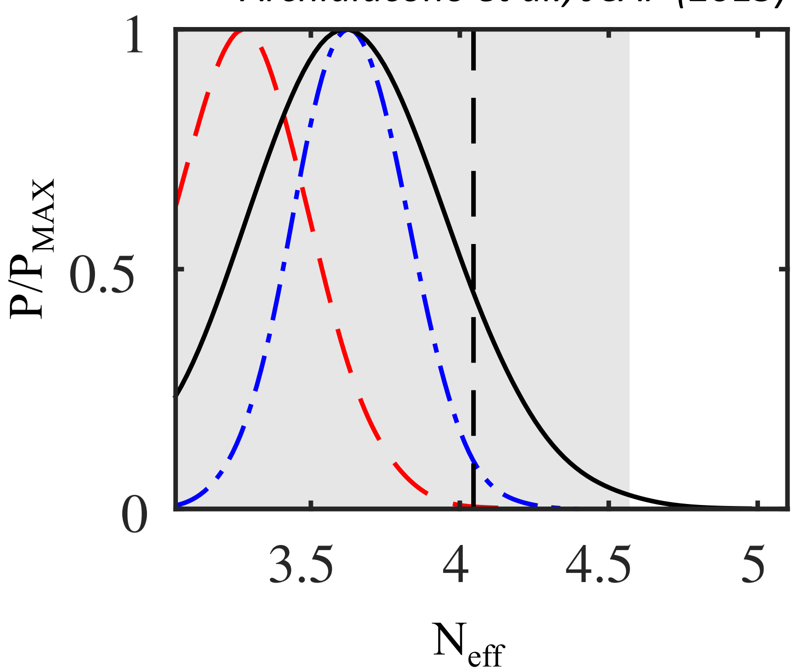
The transition between full thermalization and no thermalization occurs for coupling $10^{-6} < g_s < 10^{-5}$

N_{eff} at CMB

The $\nu_s - \phi$ fluid becomes strongly interacting before neutrinos go non-relativistic around recombination.

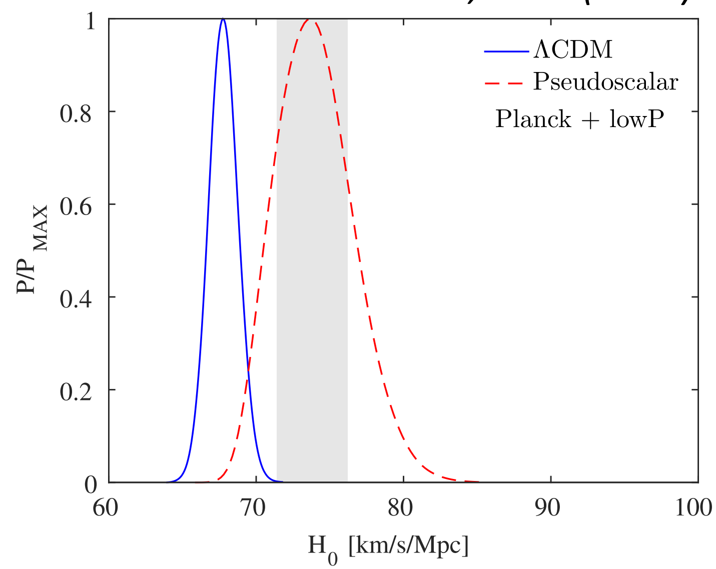
$$\Gamma_s = \frac{g_s^4}{4\pi T_s^2} n_s$$

Archidiacono et al., JCAP (2015)



Correlation between values of N_{eff} and values of g_s

Archidiacono et al., JCAP (2015)

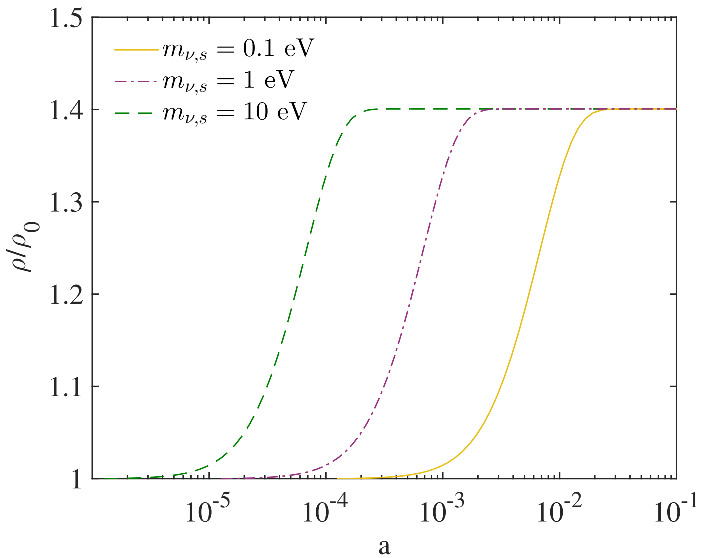


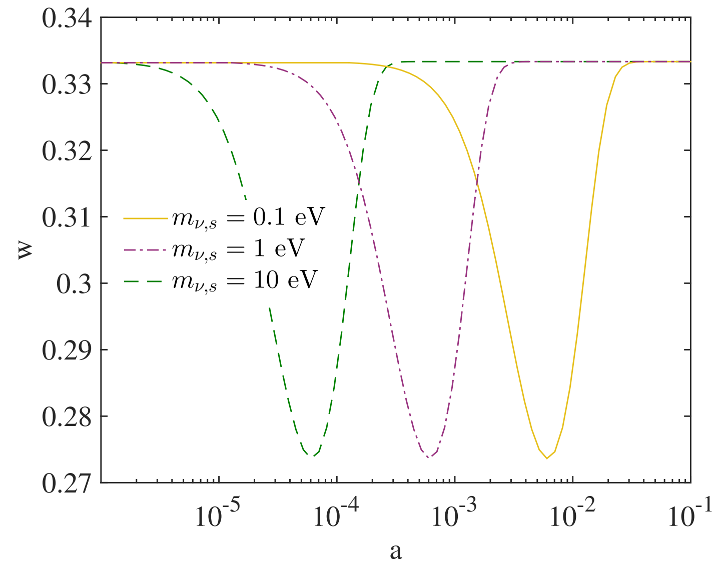
Consistent with HST

Σm_ν and LSS

As soon as sterile neutrinos go non-relativistic, they start annihilating into pseudoscalars.

Archidiacono et al., JCAP (2015)



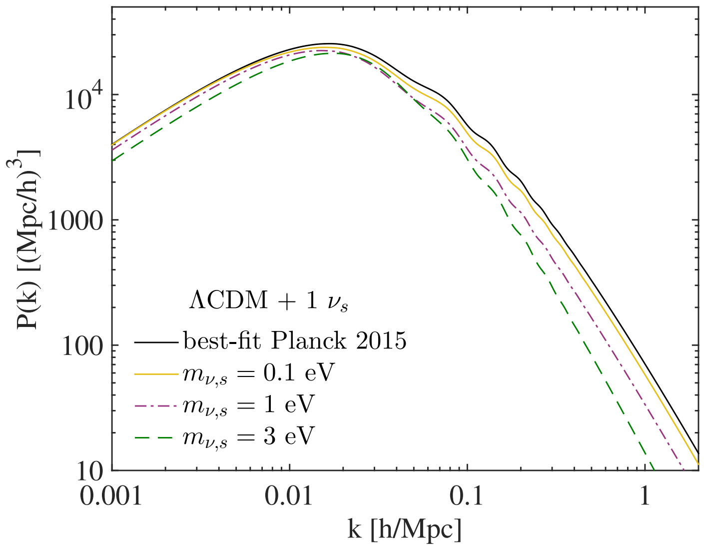


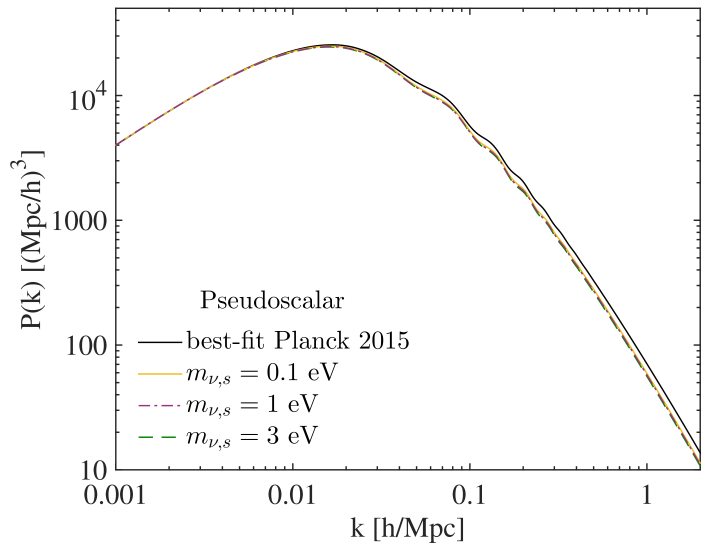
Σm_ν and LSS

Sterile neutrinos disappear from the cosmic neutrino background.

Neutrinoless Universe, Beacom et al., PRL (2004)

Archidiacono et al., JCAP (2015)





If the mediator is a massive MeV vector boson, then the late time phenomenology is different.

Hannestad et al., PRL(2013); Bringmann et al., JCAP (2014); Mirizzi et al., PRD (2014); Chu, Dasgupta, Kopp, JCAP (2015)

Galactic dynamics

Talk by Sebastian Wild
No significant self-interaction expected from pseudoscalar exchange

$$\frac{\tau_{scat}}{\tau_{dyn}} = \frac{2R^2}{3N_\chi \sigma} \left\{ \begin{array}{lll} \tau_{dyn} = \dfrac{2\pi R}{v} & \tau_{scat} = \dfrac{1}{n\langle \sigma |v| \rangle} & N_\chi = \dfrac{M_{gal}}{m_\chi} \end{array} \right.$$

Hard scattering $\quad \sigma \sim 4\pi b^2 \quad \frac{1}{2} m_\chi v^2 = \frac{\alpha_d}{m_\chi b^3} \quad \alpha_d = \frac{g_d^2}{4\pi}$

The condition for having observable consequences on galactic dynamics is that the scattering time scale of DM self interactions is less than the age of the Universe.

Milky Way:

$$g_d \geq 6 \times 10^{-8} \left(\frac{m_\chi}{MeV} \right)^{9/4}$$

It is just a lower bound
It requires further investigation

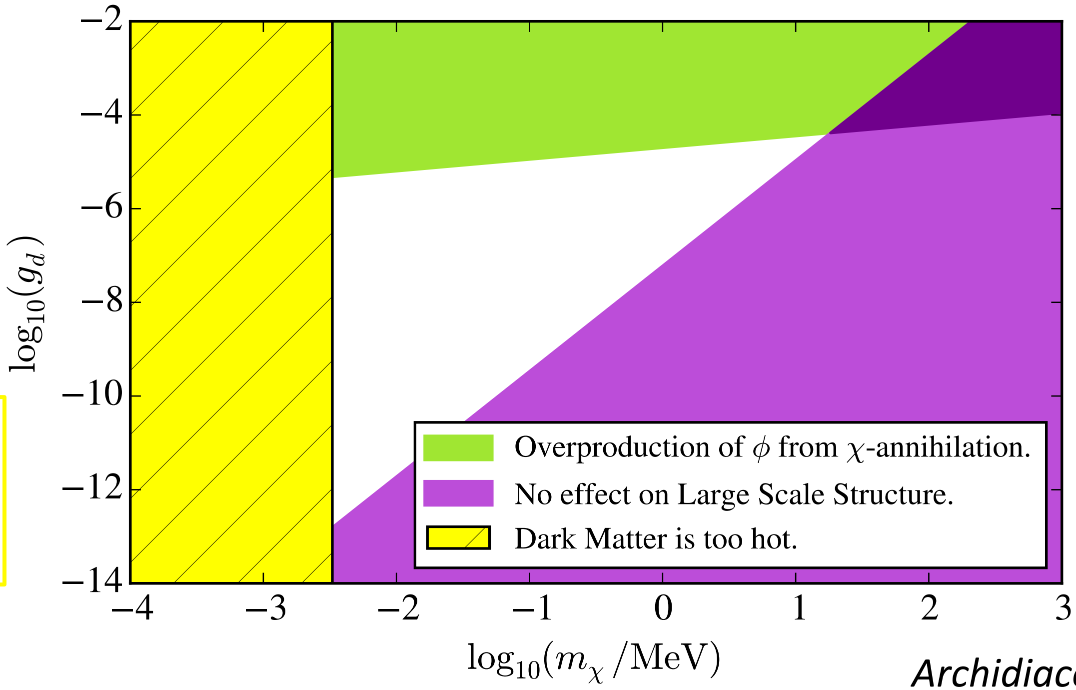
Bellazzini et al., PRD (2013)
Ackerman et al., PRD (2009)

Small scale problems

$$\Gamma_d(T) = \langle \sigma |v| \rangle n \propto g_d^4 T$$

$$\Gamma_d(T_{MAX} = m_\chi / 3) < H(T_{MAX} = m_\chi / 3)$$

$$g_d \leq 2 \times 10^{-5} \left(\frac{m_\chi}{MeV} \right)^{1/4}$$



$$g_d \geq 6 \times 10^{-8} \left(\frac{m_\chi}{MeV} \right)^{9/4}$$

WDM limit
m_χ > 3.3 keV
Viel et al. (2013)

Archidiacono et al., PRD (2014)

Conclusions & Overview

	Missing satellites	Cusp vs. core	Too big to fail
Baryons	✓	✓	✓
SIDM	✗	✓	✓
SIDM + DR	✓	✓	✓

DR = Sterile neutrinos

- Astrophysical observations
- SBL sterile neutrinos in cosmology (BBN, CMB & LSS)

Conclusions & Overview

	Missing satellites	Cusp vs. core	Too big to fail
Baryons	✓	✓	✓
SIDM	✗	✓	✓
SIDM + DR	✓	✓	✓
WDM	✓	✗	✓

Warm Dark Matter

Free-streaming length circa the size of a dwarf galaxy.
Motivated by particle physics models of sterile neutrinos.
Severely constrained by Ly-α.

Viel et al., PRD (2013)
Lovell et al., MNRAS (2014)

Conclusions & Overview

	Missing satellites	Cusp vs. core	Too big to fail
Baryons	✓	✓	✓
SIDM	✗	✓	✓
SIDM + DR	✓	✓	✓
WDM	✓	✗	✓
DDM	✓	✗	✓

Decaying Dark Matter

It is a natural way to generate a mixture of cold and warm dark matter that alters structure formation only in the late Universe, so it can evade constraints from Ly-α ($\tau \sim H_0^{-1}$).

Wang et al., MNRAS (2014)

Conclusions & Overview

	Missing satellites	Cusp vs. core	Too big to fail
Baryons	✓	✓	✓
SIDM	✗	✓	✓
SIDM + DR	✓	✓	✓
WDM	✓	✗	✓
DDM	✓	✗	✓
LFDM	✓	✗	✓

Late Forming Dark Matter

Phase transition of a scalar field from radiation to matter (fuzzy dark matter is a form of LFDM). The earlier the phase transition, the smaller the power spectrum cutoff scale.

Agarwal et al., PRD (2015)

Ultra Light Axions & Ly-α, *Kobayashi et al., (2017)*

Conclusions & Overview

	Missing satellites	Cusp vs. core	Too big to fail
Baryons	✓	✓	✓
SIDM	✗	✓	✓
SIDM + DR	✓	✓	✓
WDM	✓	✗	✓
DDM	✓	✗	✓
LFDM	✓	✗	✓
BSI	✓	✓	✗

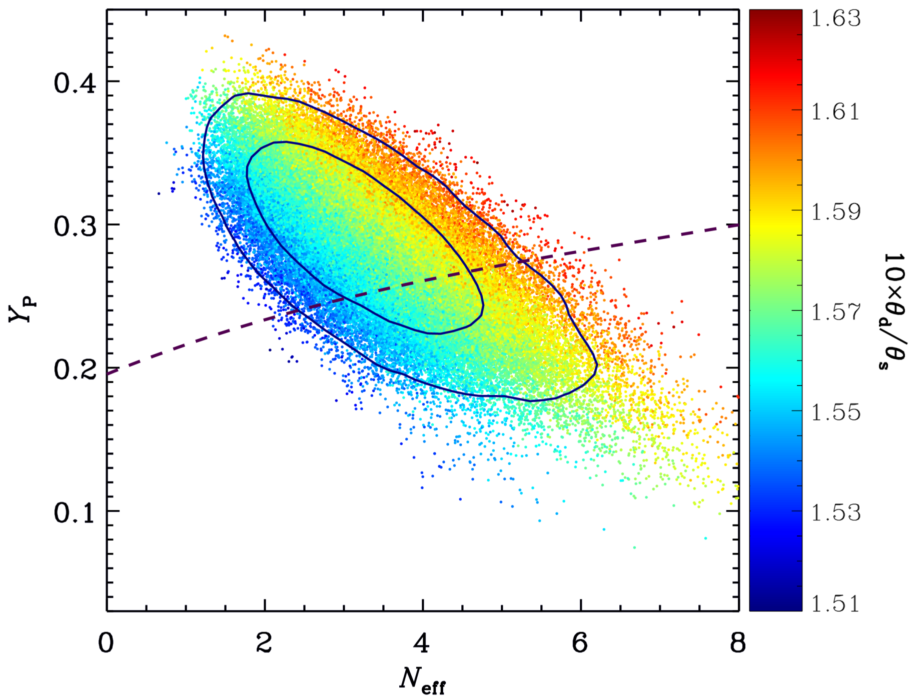
Broken-Scale-Invariance inflationary model

The model predicts an excess of power wrt to ΛCDM before the cutoff; thus it is highly constrained by Ly-α.

Kamionkowski et al., PRL (2000)

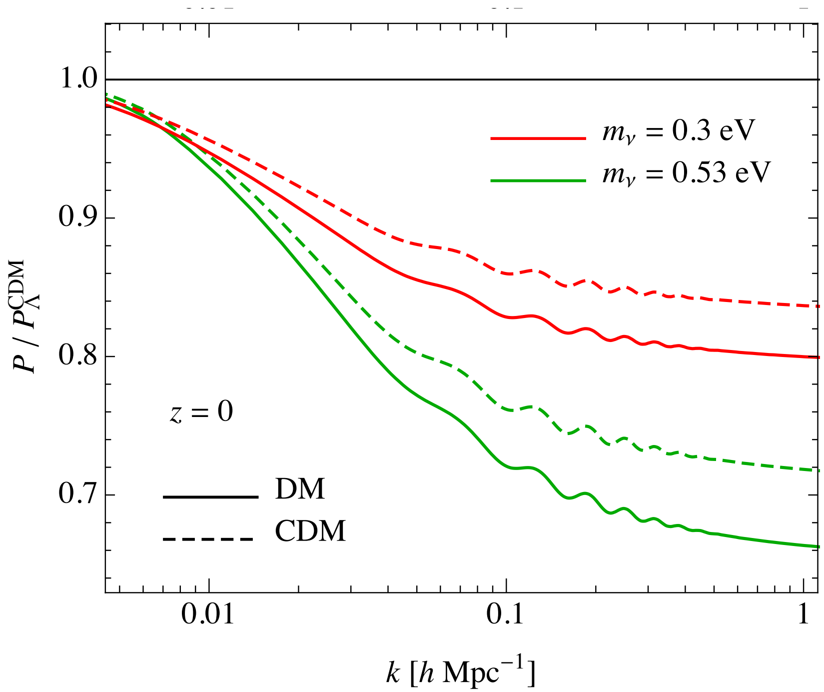
Backup

N_{eff} & Y_P



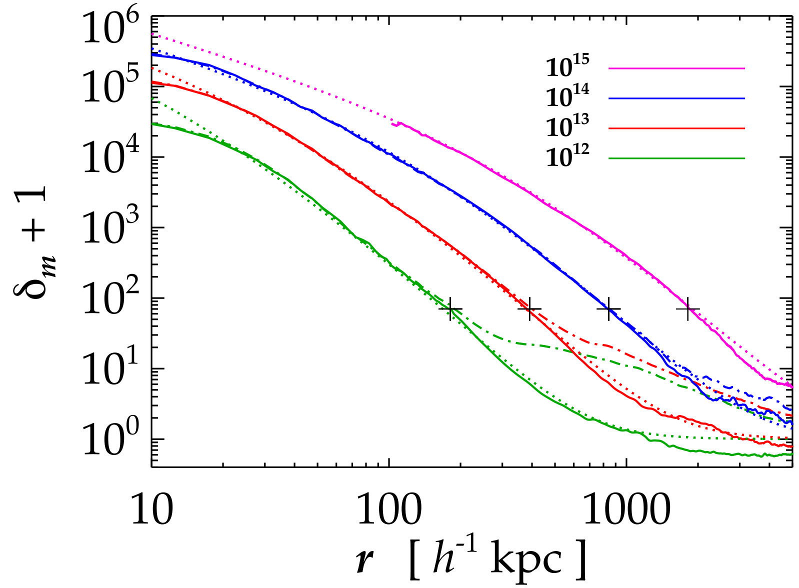
Hou et al., PRD (2013)

Massive neutrinos & P(k)



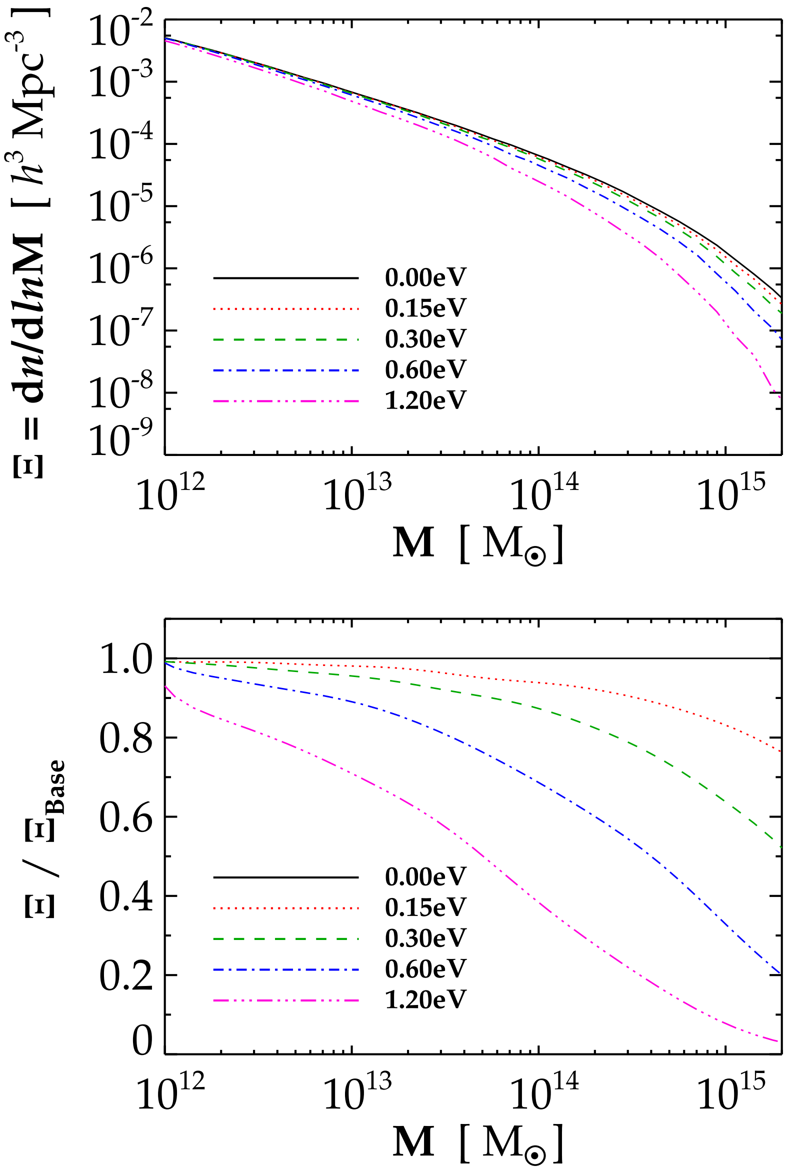
Castorina et al., JCAP (2015)

Massive neutrinos & Halo profile



Brandbyge et al., JCAP (2010)

Massive neutrinos & HMF

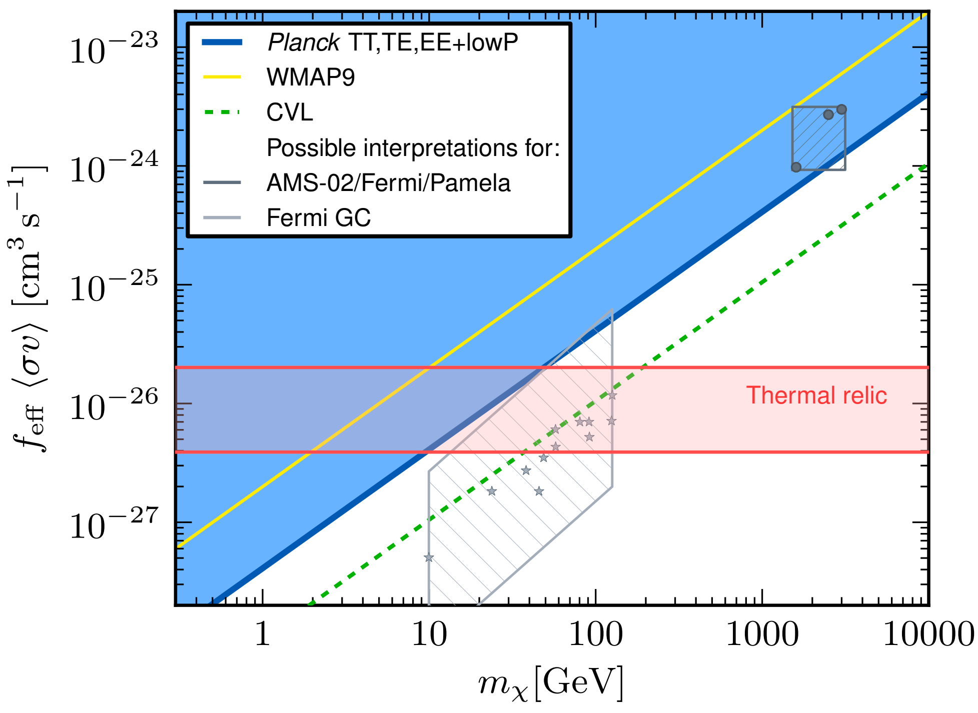


Brandbyge et al., JCAP (2010)

CMB & annihilation cross section

$$\frac{dE}{dtdV}(z) = 2\,g\,\rho^2_{\rm crit}c^2\Omega^2_{\rm c}(1+z)^6 p_{\rm ann}(z),$$

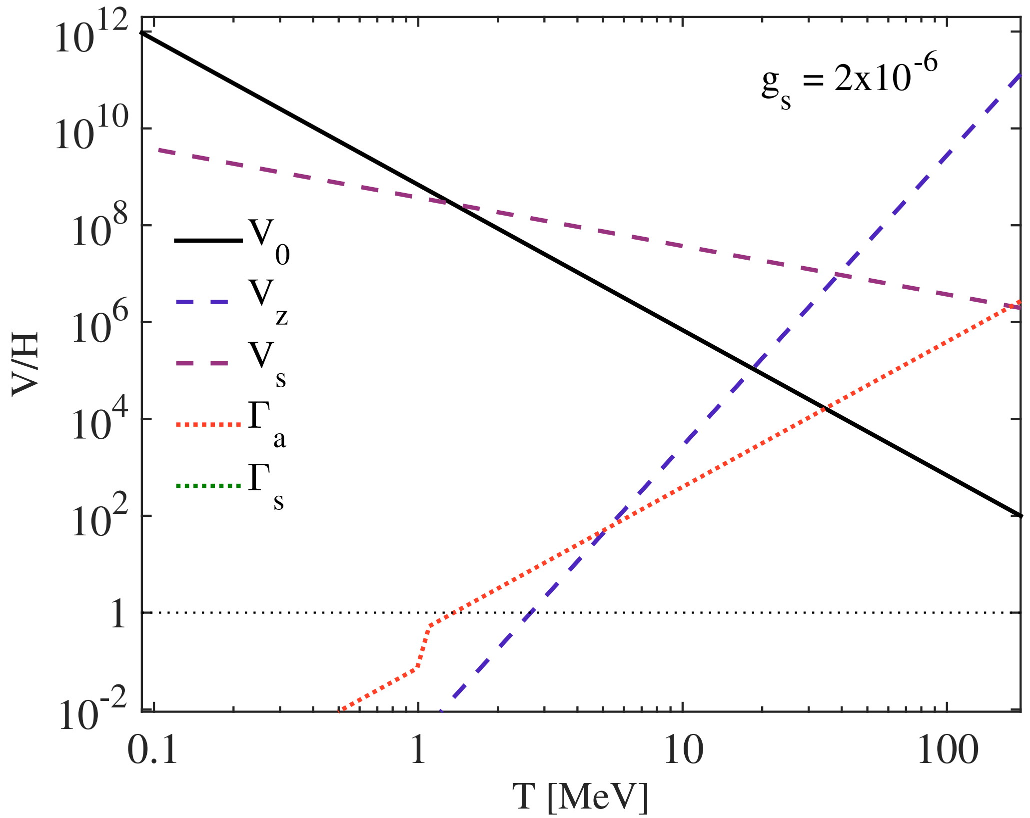
$$p_{\rm ann}(z) \equiv f(z)\frac{\langle\sigma v\rangle}{m_\chi},$$



CMB: $v/c \sim 10^{-8}$

Flavour oscillations

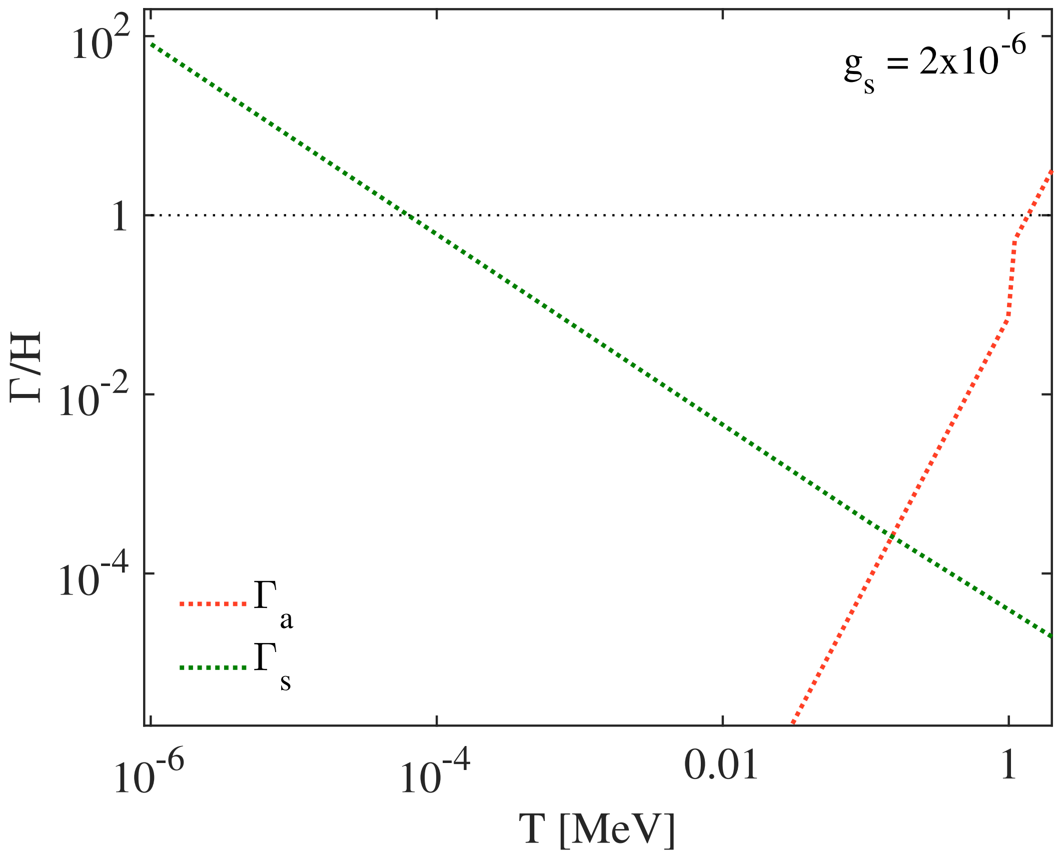
$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos 2\theta_0 + \frac{2E}{\Delta m^2} V_{\rm eff}\right)^2 + \sin^2 2\theta_0}$$



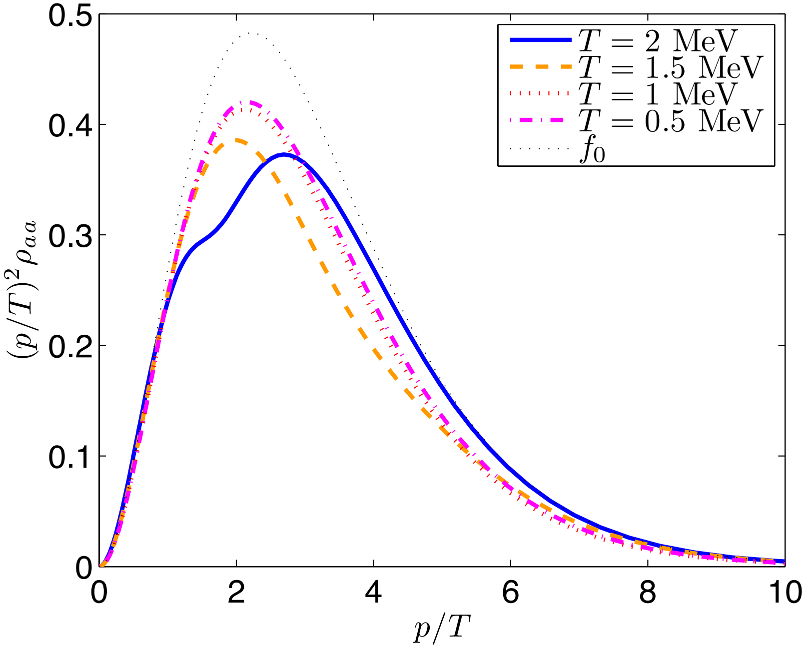
Collisional re-coupling

$$\Gamma_{\rm coll} = n_{\nu_s}\sigma \sim \begin{cases} n_{\nu_s} e_s^4 \frac{E^2}{M^4} & \text{for } T_s \ll M \\ n_{\nu_s} e_s^4 \frac{1}{E^2} & \text{for } T_s \gg M \end{cases}$$

$$\Gamma_s \simeq \frac{1}{2}\sin^2 2\theta_m \times \frac{3}{4} n_{\nu_a}^{\rm SM} \cdot \begin{cases} e_s^4 \frac{E^2}{M^4} & \text{for } T_s \ll M \\ e_s^4 \frac{1}{E^2} & \text{for } T_s \gg M \end{cases}$$



Neutrino PDF



Hannestad et al., PRL (2013)

DM-pseudoscalar

$$V(r) = -\frac{g_d^2}{m_\chi^2} \frac{e^{-m_\phi r}}{4\pi r^3} h(m_\phi r) \mathcal{S},$$

$$h(m_\phi, r) \, = \, 1 + m_\phi r + \tfrac{1}{3}(m_\phi r)^2$$

Sommerfeld & pseudoscalar