DSU 2016, Univ. of Bergen

29 July 2016

Small-scale Structure and Interacting Dark Matter & Dark Radiation

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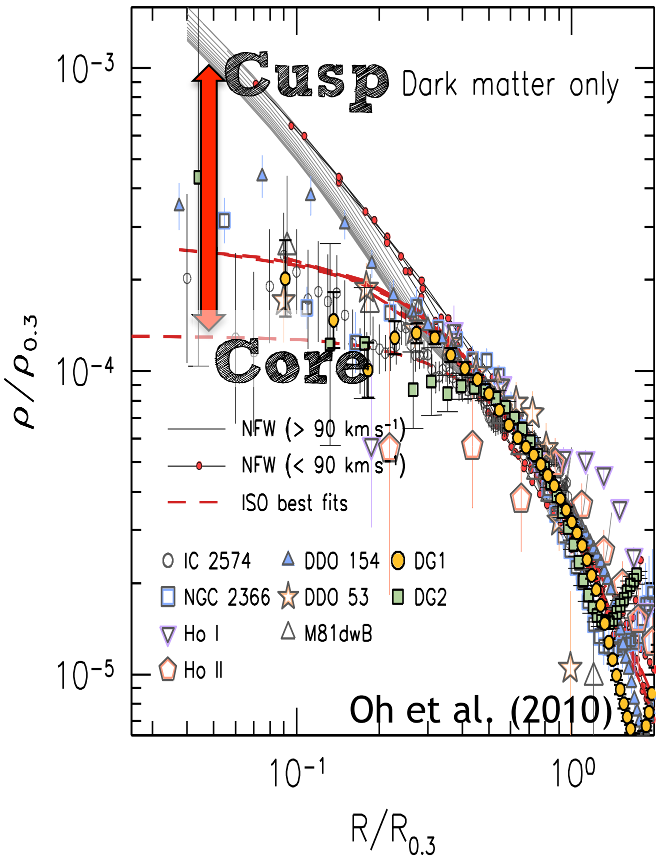
TIFR, Mumbai

Does DM have Interactions?

Core-Cusp

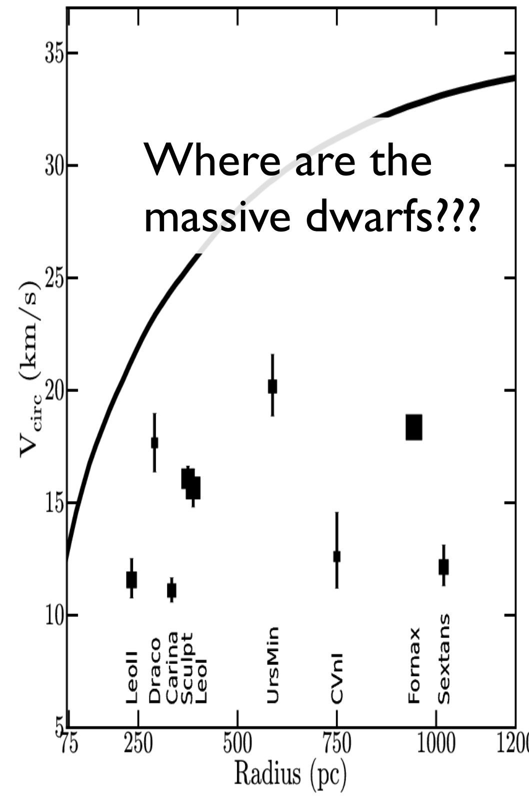


Moore (1994);
Flores and Primack (1994)

Missing Satellites

Klypin, Kravstov, Valenzuela, and Prada (1999)

Too Big to Fail



Boylan-Kolchin, Kaplinghat, Bullock (2010)

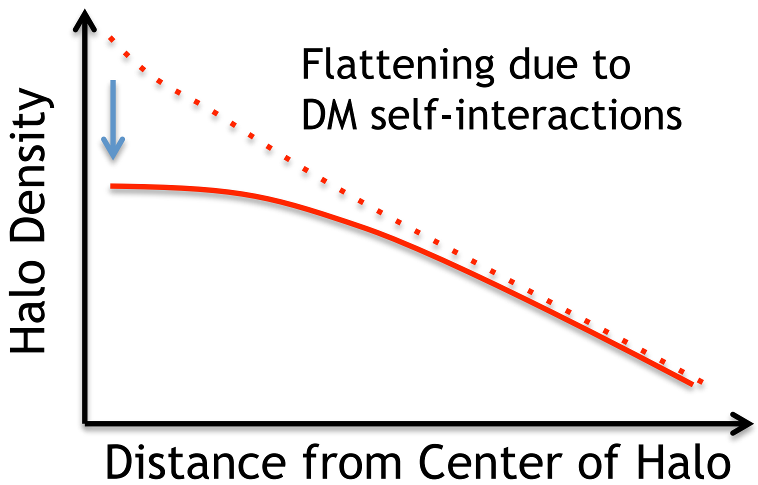
How to improve structures ?

- Supernova feedback (blows out gas, no stars)
- Tidal effects (strips out small halos)
- Low star-formation (small halos have less stars)

While these astrophysical solutions are plausible, it is not yet established that they address all the problems to the extent required (e.g., dwarf galaxies have lower metallicity and feedback is expected to be lower). On the other hand, one may question the data itself. This remains a topic of intense debate ☺

- Can particle physics address these issues? If so, what kind of models would we need? How would we test these models?

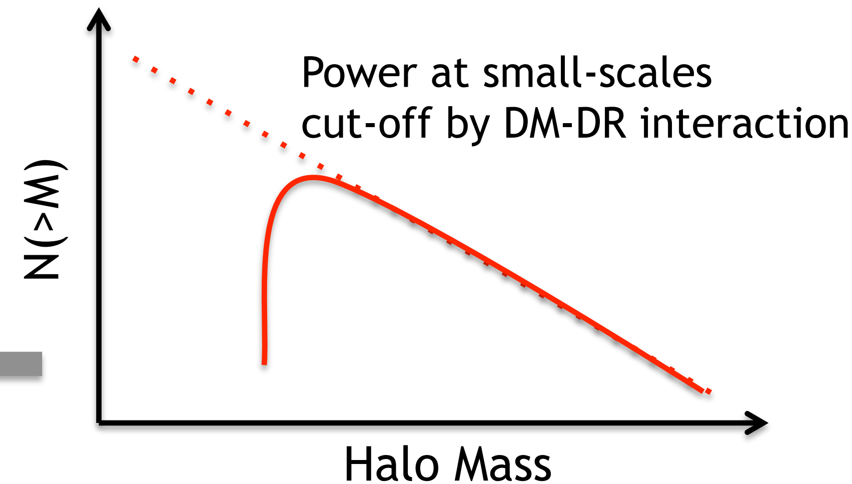
Simultaneous Solutions to Small Scale Structure Problems of Lambda-CDM



Too-Big-to-Fail Problem and the Core-Cusp Problem solved using DM self-interactions that smoothen DM density

Spergel and Steinhardt (1999)

Talk by Kai Schmidt-Hoberg



Missing Satellites Problem solved using DM interactions with a radiation-like species that delays kinetic decoupling

Boehm, Fayet, and Schaeffer (2001)
Loeb and Zaldarriaga (2005)
Bringmann and Hofmann (2005)

Smoothening DM Cusps

Dwarf-sized halos do not have cusps due to DM-DM interactions mediated by A'.

What one needs is then DM-DM scattering cross section at the level of 0.1 cm^2 / g for velocities of dwarf galaxies (10 km/s).

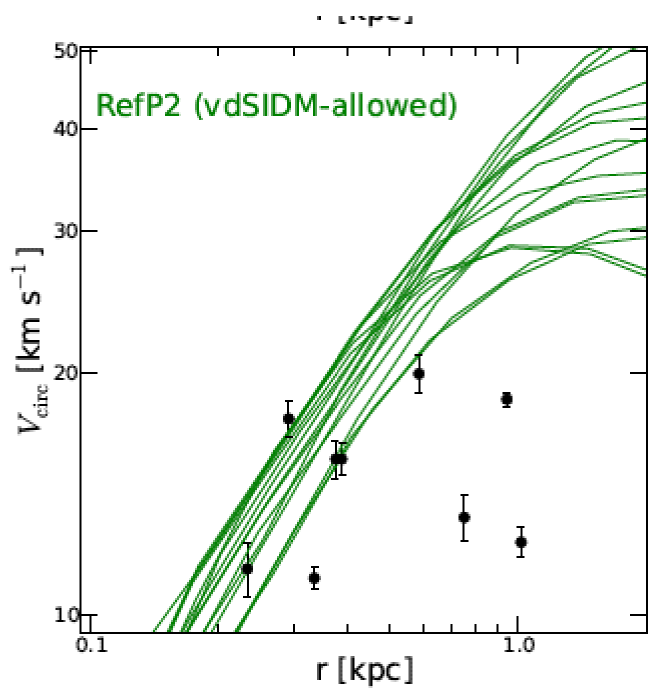
Feng, Kaplinghat, Tu, Yu (2009); Loeb and Weiner (2011)

This is easily achieved by having a light mediator A' that enhances the cross section.

Addressing the TBTF problem

Dwarf-sized subhalos inside MW do not have cusps due to DM-DM interactions mediated by A'.

What one needs is then DM-DM scattering cross section at the level of 0.1 cm^2 / g for velocities of dwarf galaxies (10 km/s). This is the same condition as that for solving the core-cusp problem.



Zavala, Vogelsberger, Loeb (2012)

Explaining the Missing Satellites

The sterile neutrino-DM scattering keeps DM in kinetic equilibrium until somewhat later $(T_\chi/m_\chi\, n_\nu\, \sigma_{\nu\chi}) \sim H$

This erases structure at the smallest scales, and the smallest (dwarf) halos never form.

Boehm, Fayet, Schaeffer (2000); Loeb and Zaldarriaga (2005)

What one needs is then M_cut ~ 10^9 solar masses or so.

$$\frac{M_{\rm cut}}{M_{\rm Sun}} \simeq 3.2 \times 10^{13}\, \alpha_\chi^{\frac{3}{2}} \left(\frac{T_s}{T_\gamma}\right)_{\rm kd}^{\frac{9}{2}} \left(\frac{\rm TeV}{m_\chi}\right)^{\frac{3}{4}} \left(\frac{\rm MeV}{M}\right)^{3}.$$

One needs a spin-1 mediator for this to work. Scalars lead to a small effect.

Dark Radiation Candidates

- Many possibilities with good motivations …
  - Thermal QCD axions (Strong CP)
  - Hidden Photons (Dark U(1), …)
  - Sterile Neutrinos (eV scale)
  - Goldstone Bosons (broken Global symmetry)

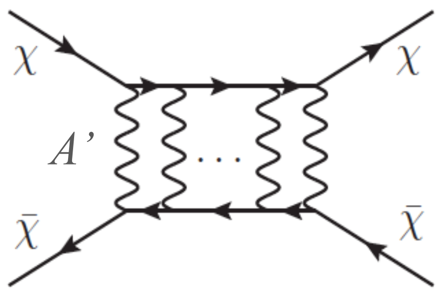
Two Types of Models

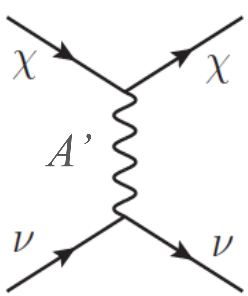
See Bringmann et al. (2016) for EFT-type treatment
Hannestad++ (2015, 2016) for Pseudo-scalar mediators
…

DM Self-Interactions

DM-DR Interactions

DM + (Sterile) Neutrinos + A'

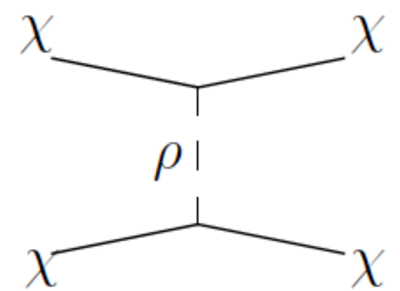


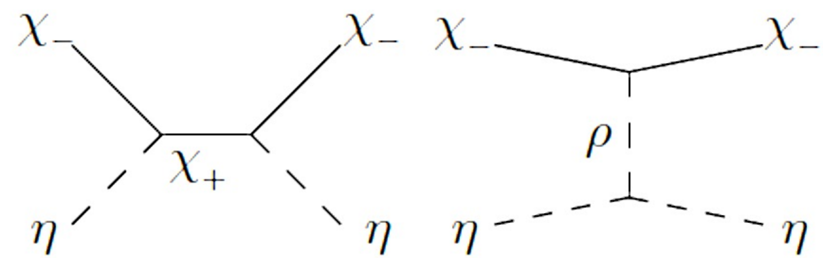


DM-Neutrino Interactions

van den Aarssen, Bringmann, Pfrommer (PRL, 2012)
Hannestad, Hansen, Tram (PRL, 2014)
Dasgupta and Kopp (PRL, 2014)
Bringmann, Hasenkamp, Kersten (JCAP, 2014)

Pseudo-Dirac DM + Complex Scalar





DM-Goldstone Interactions

Weinberg (PRL, 2012)
Garcia-Cely, Molinari, Ibarra (JCAP, 2013)
Chu and Dasgupta (PRL, 2014)

Recent Developments

DM + (Sterile) Neutrinos + A'

Heavy A' (~100 MeV) in conflict with BBN

Saviano, Pisanti, Mangano, Mirizzi (PRD, 2014)

Light A' (< 10 MeV) in conflict with LSS

Mirizzi, Mangano, Pisanti, Saviano (PRD, 2014)

Neutrino interactions delay free-streaming and evade LSS bound

Chu, Dasgupta, Kopp (JCAP, 2015)

But now CMB bound on free-streaming becomes too constraining

Archidiacono and Hannestad (JCAP, 2014)

More careful treatment of collisional production leads to stronger constraints

Cherry, Friedland, Shoemaker (2016)

Pseudo-Dirac DM + Complex Scalar

Appears to be viable with GeV DM, MeV mediator and a Goldstone DR

Testable via N_eff at next generation CMB experiments

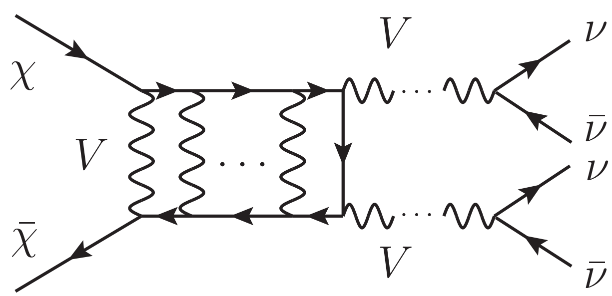
Chu and Dasgupta (PRL, 2014)

Finite Temperature and Sommerfeld corrections appear to be important

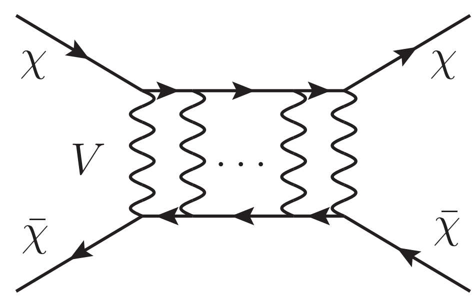
Das and Dasgupta (to appear)

We will now discuss some of these results in more detail

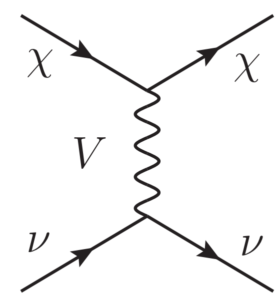
Neutrinophilic DM Models



Relic Annihilation



Self-Scattering



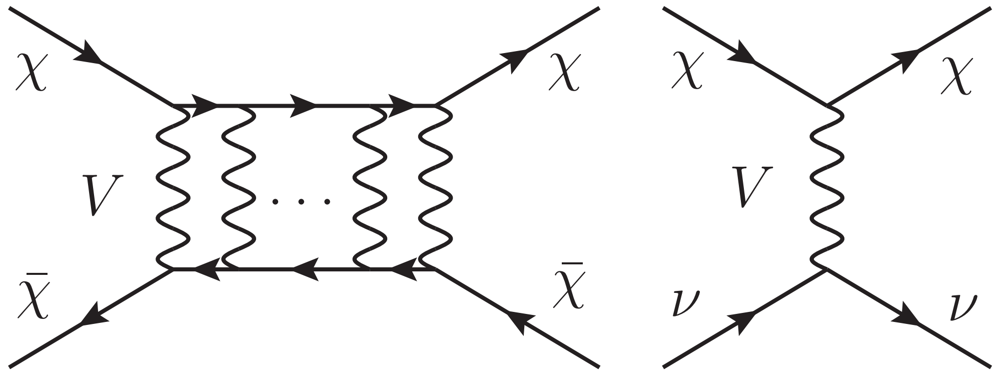
Late-Decoupling

DM and Neutrinos share a common new interaction

Somewhat simpler to use sterile neutrinos instead!
To avoid issues with DM-charged lepton interactions.

vanDen Aarssen, Bringmann, Pfrommer (2012)

Neutrinos vs. Steriles



Self-Scattering **Late-Decoupling**

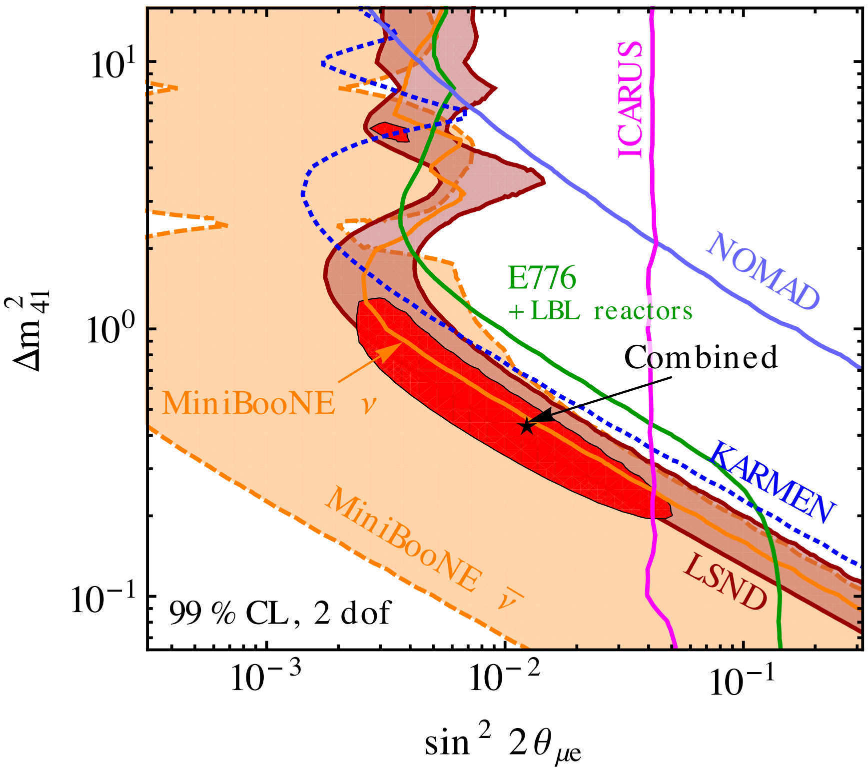
Sterile nus anyway benefit from an interaction – they become cosmologically viable.

Hannestad, Hansen, Tram (2014)
Dasgupta and Kopp (2014)

Same interaction rescues DM.

Dasgupta and Kopp (2014)
Also, Bringmann, Hasenkamp, Kersten (2014) and Ko, Tang (2014)

Sterile Neutrinos at 1eV



Global fit to all appearance data is consistent, and 3+2 or 1+3+1 models are better fits than 3 only or 3+1.

Machado, Kopp, Maltoni, Schwetz (2013)

+ similar results by
Palazzo;
Giunti, Laveder, et al;
Conrad et al., …

If one takes the neutrino oscillation anomalies seriously, one needs 1 or 2 sterile neutrinos with large mixings

Cosmological Sterile Neutrinos

- Vacuum mixing (Dodelson-Widrow)
  - Usual mixing of active-sterile.
  - Hot sterile nus.
- Resonant production (Shi-Fuller)
  - Steriles produced only via a MSW resonance that needs a large lepton asymmetry.
  - Cold/Warm sterile nus.
- …

Effective m and N

Often the temperature of the active neutrinos and the sterile neutrinos are not the same.

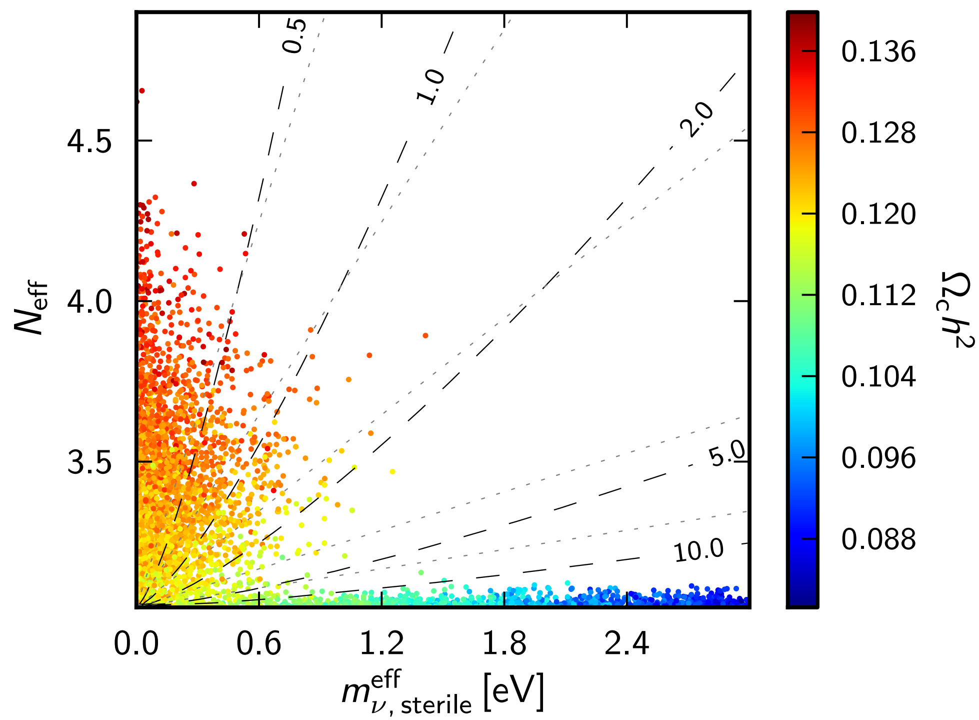
Even if sterile neutrinos were in equilibrium at some early temperature, the decay of SM (or Sterile) sector particles can lead to different temperatures.

Say the two were in thermal equilibrium above ~TeV, then

$$T_s = \left(\frac{g_*(T_\gamma)}{g_*(\mathrm{TeV})} \right)^{1/3} T_\gamma$$

So effective number and energy densities of sterile neutrinos can be different (lower). But typically oscillations bring them back in equilibrium, and this suppression is absent.

Endangered Sterile Neutrinos



Oscillation-friendly neutrinos are in tension with cosmology

$$\left.\begin{aligned} N_{\rm eff} &< 3.80 \\ m^{\rm eff}_{\nu,\,\rm sterile} &< 0.42\,{\rm eV} \end{aligned}\right\} \quad (95\%;\ {\rm CMB{+}BAO\ for}\ m^{\rm thermal}_{\rm sterile} < 10\,{\rm eV})\,. \tag{83}$$

These bounds are only marginally compatible with a fully thermalized sterile neutrino ($N_{\rm eff} \approx 4$) with sub-eV mass $m^{\rm thermal}_{\rm sterile} \approx m^{\rm eff}_{\nu,\,\rm sterile} < 0.5\,{\rm eV}$ that could explain the oscillation anomalies.

Planck Collaboration (2013)

Ways to avoid the constraint

- Large lepton asymmetry
  - Foot and Volkas (1995)
- Majorons
  - Babu and Rothstein (1992), Bento and Bereziani (2001),
- Very low reheating temperature
  - Gelmini, Palomarez-Ruiz, Pascoli (2004)
- Dilution by decay of exotic heavy particles
  - Fuller, Kishimoto, Kusenko (2011), Ho and Scherrer (2012), …
- ...

The Not-So-Sterile Neutrino

$$\mathcal{L} = e_\nu \overline{\nu_s} \gamma_\mu \nu_s A'_\mu$$

Add to SM a sterile neutrino that has some gauge interaction via a new light gauge boson A.

Initially sterile and active sectors in equilibrium, and decouple at T > 100 GeV.

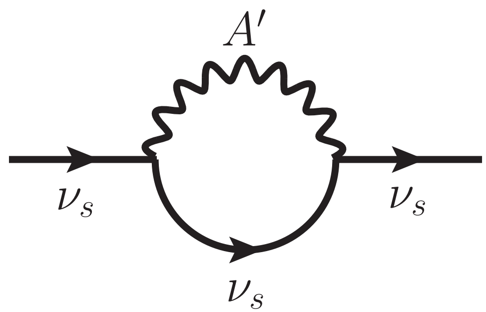
Because of energy injection into photons, $T_s = \left(\frac{g_*(T_\gamma)}{g_*(\mathrm{TeV})} \right)^{1/3} T_\gamma$

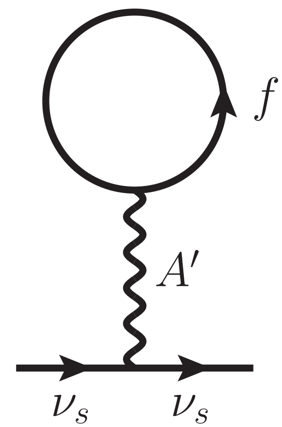
Leads to extra N_eff ~0.5 by BBN thermally.

What about oscillations?

Hansen, Hannestad, Tram (2014)
Dasgupta and Kopp (2014)

Thermal Masses

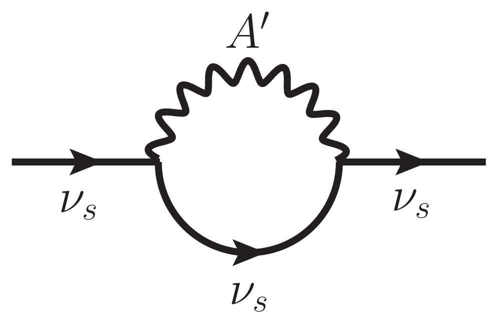




Sterile neutrinos acquire a "thermal mass" due to their interactions with virtual/real gauge bosons which can be quite large at high-T.

They are not produced by oscillations if this mass exceeds the active-sterile neutrino oscillation frequency.

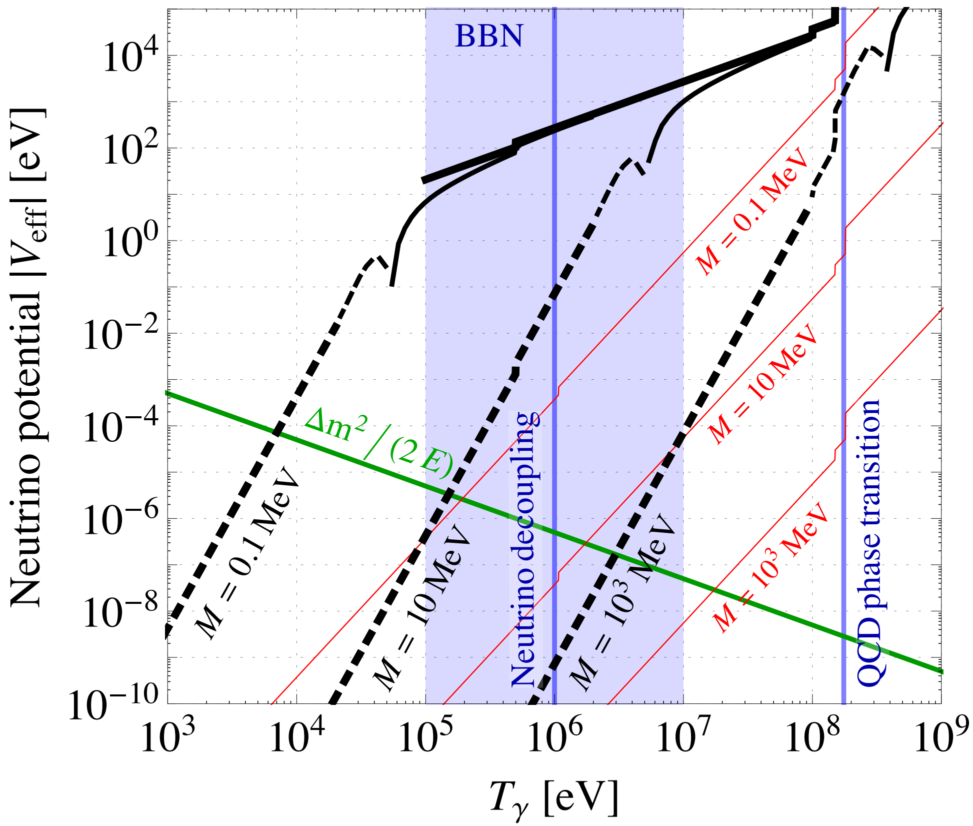
Thermal Masses



$$V_{\rm eff}^{\rm bubble} \simeq \begin{cases} -\dfrac{28\pi^3\alpha_\chi E T_s^4}{45 M^4} & \text{for } T_s, E \ll M \\ +\dfrac{\pi\alpha_\chi T_s^2}{2E} & \text{for } T_s, E \gg M \end{cases}$$

Purely thermal contribution. Exists even with no asymmetry.

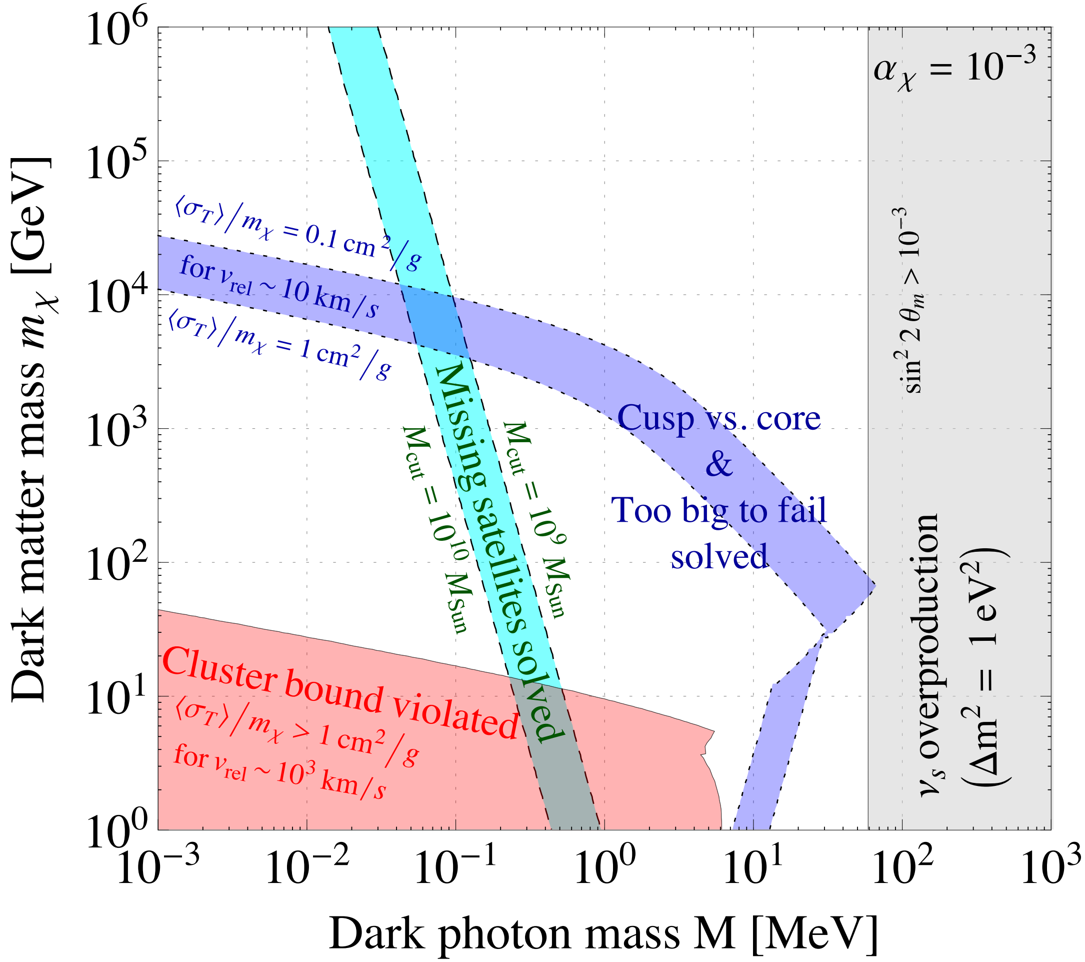
Thermal MSW Potential



If M < 10 MeV the thermal potential can be large

Dasgupta and Kopp (2014)

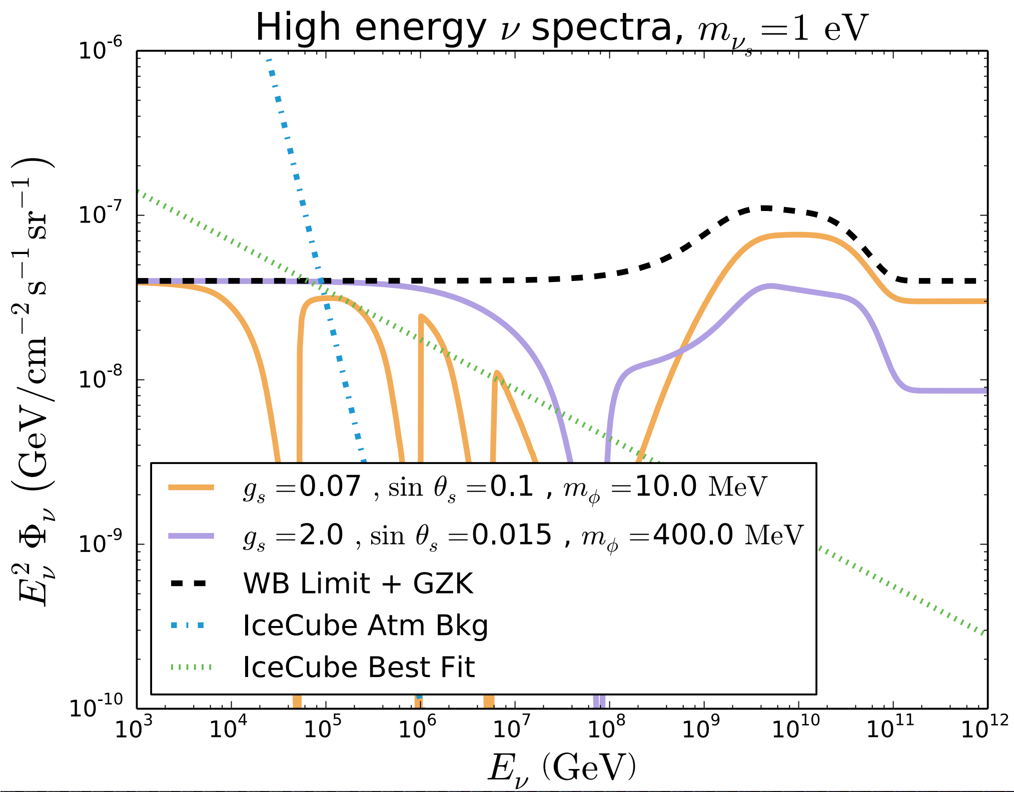
DM-Neutrino Concordance



One can explain N_{eff} , Neutrino Oscillations, and All 3 DM problems, simultaneously

Dasgupta and Kopp (2014), See also Bringmann, Hasenkamp, Kersten (2014)

A Connection to PeV Neutrinos



Can lead to depletion of HE events around a PeV at IceCube

Cherry, Friedland, and Shoemaker (2015)
Similar ideas in: Ioka and Murase (2014), Ng and Beacom (2014)

MSW suppression

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

$$|V_{\rm eff}| \gg \left|\frac{\Delta m^2}{2E}\right|$$

No production by oscillations. Also thermalization rate is similarly suppressed.

N_{eff} is increased by ~0.5 due to sterile neutrinos at BBN (much less at CMB)

Dasgupta and Kopp (2014)

Full QKE

$$\dot{\mathbf{P}} = \mathbf{V} \times \mathbf{P} - D(P_x \mathbf{x} + P_y \mathbf{y}) + \dot{P}_0 \mathbf{z} \ ,$$

$$\dot{P}_0 = \Gamma \left[\frac{f_{\rm eq}}{f_0} - \frac{1}{2}(P_0 + P_z) \right]$$

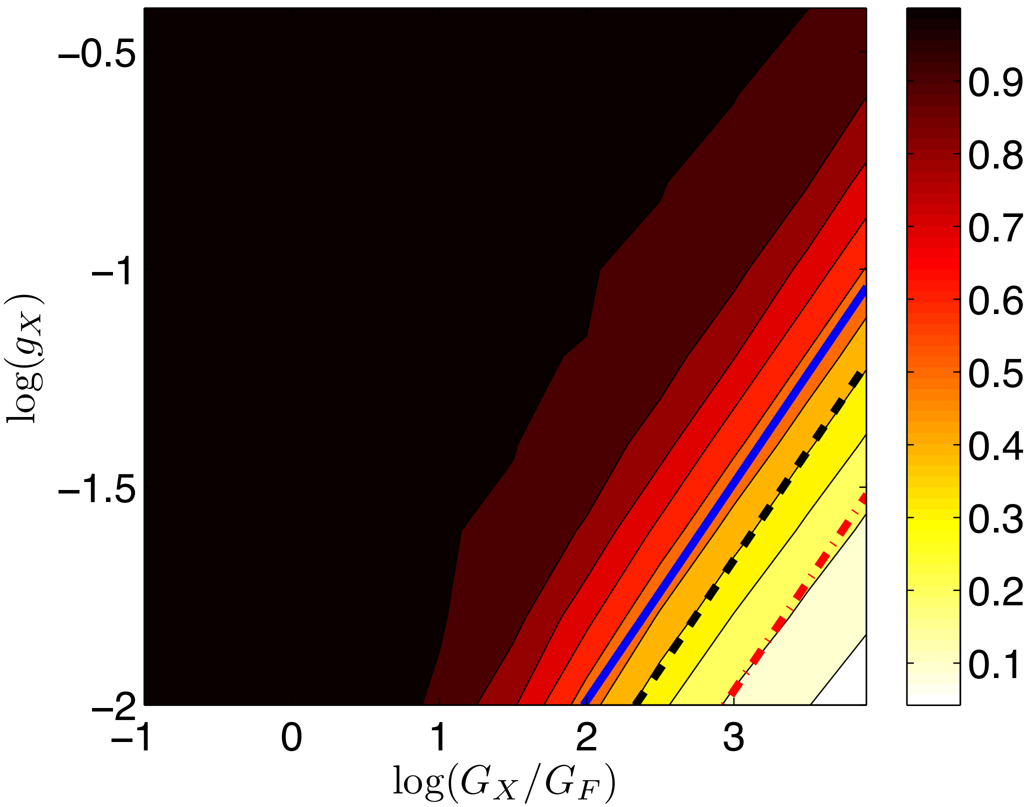
Besides oscillations, scattering processes also taken into account.
The scattering rate is

$$\Gamma = C_a G_F^2 x T^5$$

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

Hansen, Hannestad, Tram (2014)

Fractional dofs from QKE



For ~100 MeV boson
One can easily suppress
N_eff to below 0.5

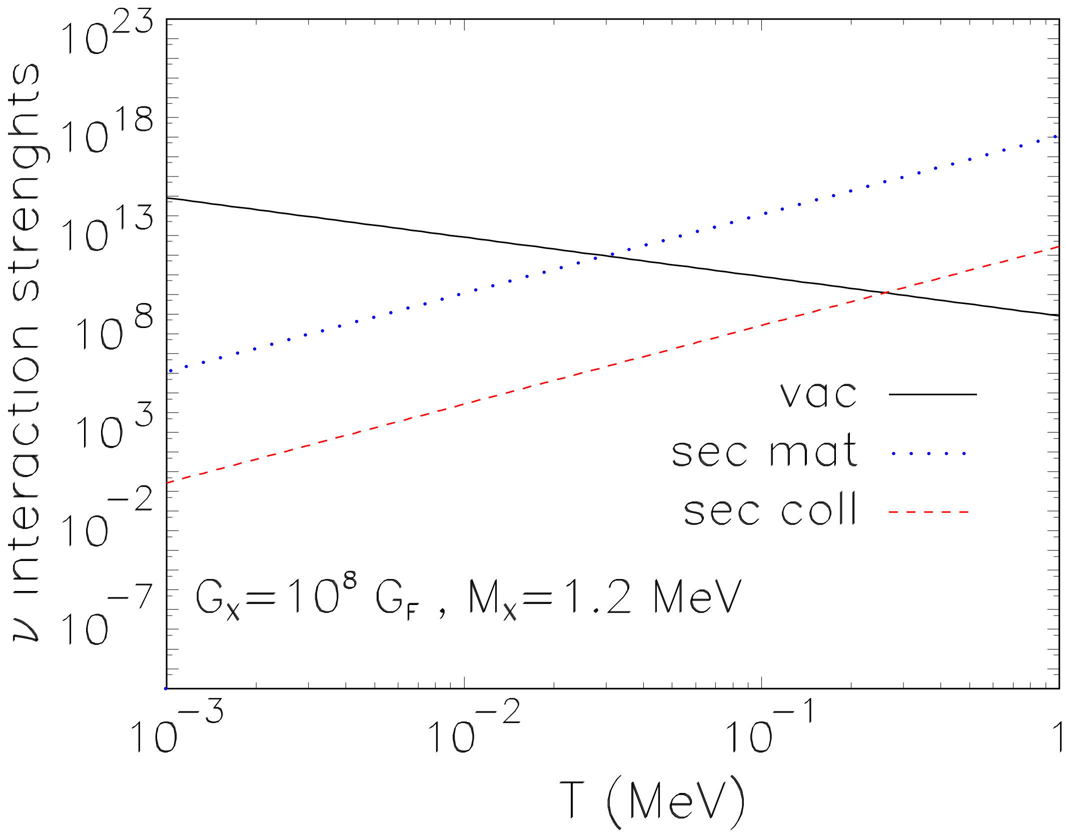
Hansen, Hannestad, Tram (2014)

Comments

- Detailed dynamics should consider MSW resonances
- Adiabaticity effects
- Non-forward scattering processes
- Sterile neutrino decoupling is slightly earlier than 1 MeV due to mixing angle suppression
- Tails of the thermal distribution
- V << T, so relativistic approximation holds
- Heavy M (~40-100 MeV) spoils BBN

Post-BBN Thermalization

Mirizzi, Mangano, Pisanti, Saviano (2014)

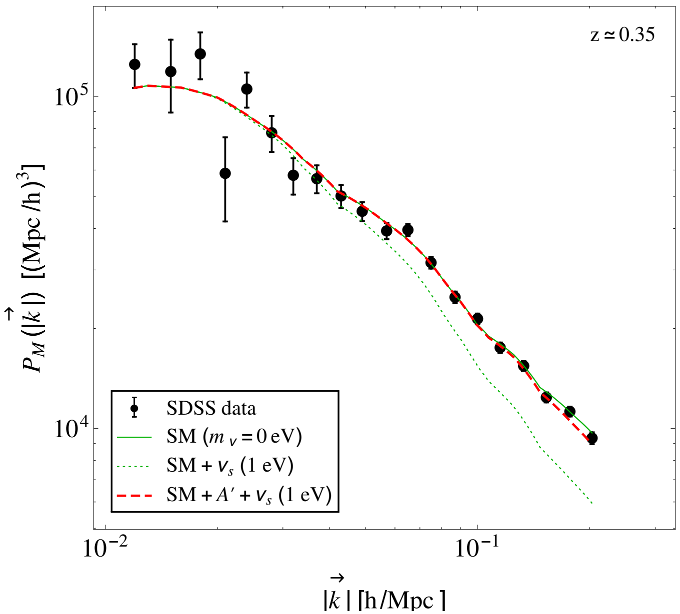


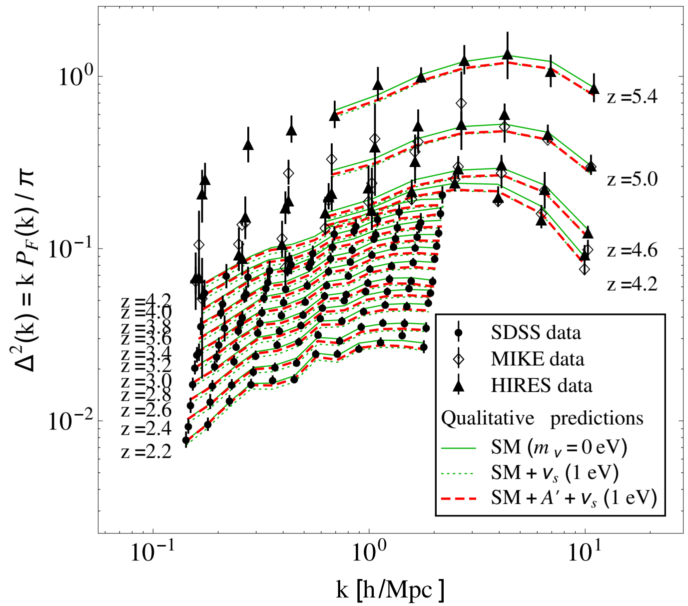
For ~1 MeV boson, one equilibrates sterile and active neutrinos through collisional decoherence

In some cases tension with mass bounds ☹

This constraint rules out almost all parameter space except two regions at M~1 MeV and g~10^-4 and at M ~ 0.1 MeV with g~0.1

Evading LSS bounds using A'





1 eV neutrinos are strongly constrained by SDSS data

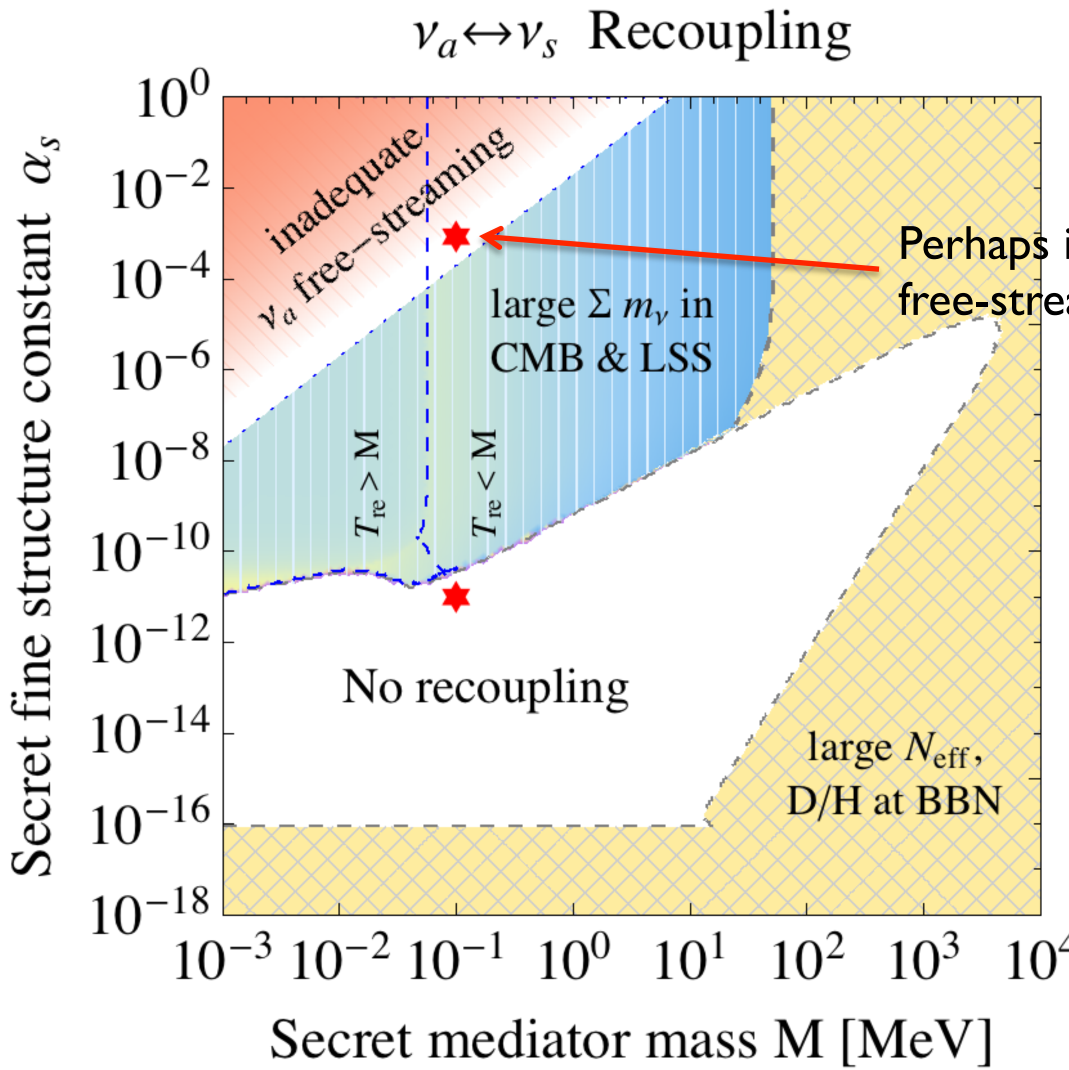
But if interacting via A' evade LSS bound by never really free-streaming until matter-radiation equality

1 eV neutrinos are strongly constrained by Lyman-Alpha data

Seem to be OK if interacting via A'

Viel et al. (2013)
Chu Dasgupta, and Kopp (2015)

Is any parameter space allowed?

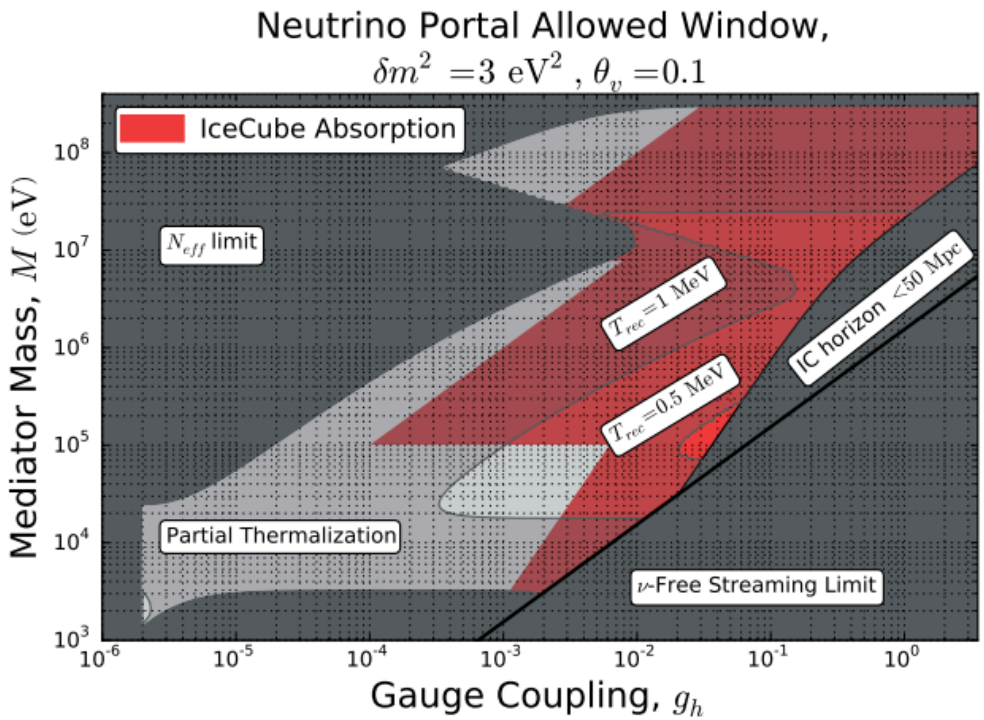


Perhaps in tension with active nu free-streaming

Archidiacono and Hannestad (2014)

Chu, Dasgupta, and Kopp (2015)

Collisional Production Revisited



Cherry, Friedland, Shoemaker (2016)

Key Point: The x-section for scattering is g^4/M^2 not g^4/T^2 at low T

This has significant impact on the parameter space and it appears prima facie that all of the parameter space is now disfavored

Ok, so if not neutrinos, then what?

Getting Rid of Neutrinos

$$\mathcal{L}_{\rm dark} \ni \partial_\mu \phi^* \partial^\mu \phi + \mu_\phi^2 |\phi|^2 - \lambda_\phi |\phi|^4$$

Complex Scalar

$$+ i\bar{\chi}\gamma^\mu \partial_\mu \chi - M\bar{\chi}\chi - (\frac{f_{\rm d}}{\sqrt{2}}\phi \chi^T C \chi + h.c.)$$

Fermion

Weinberg (2013)

On spontaneous symmetry breaking

Garcia-Cely, Ibarra, Molinaro (2013)

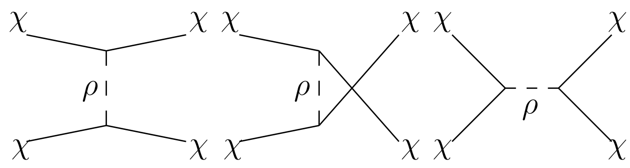
$$\phi \equiv (v_\phi + \rho + i\eta)/\sqrt{2}$$

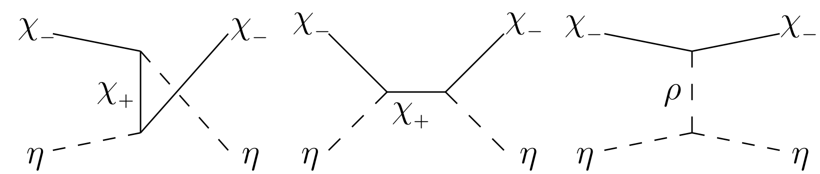
$$\chi_\pm \to -\chi_\pm \text{ and } (\rho, \eta) \to (\rho, \eta)$$

Residual Z2 symmetry ensures χ_- = DM is stable

Also η = DR

DM-DM and DM-DR Scattering





DM-DM Scattering

$$\sigma_T \simeq \frac{8\pi\alpha_{\rm d}^2}{m_\chi^2 v_{\rm rel}^4}\left[\log(1+R^2) - \frac{R^2}{1+R^2}\right]$$

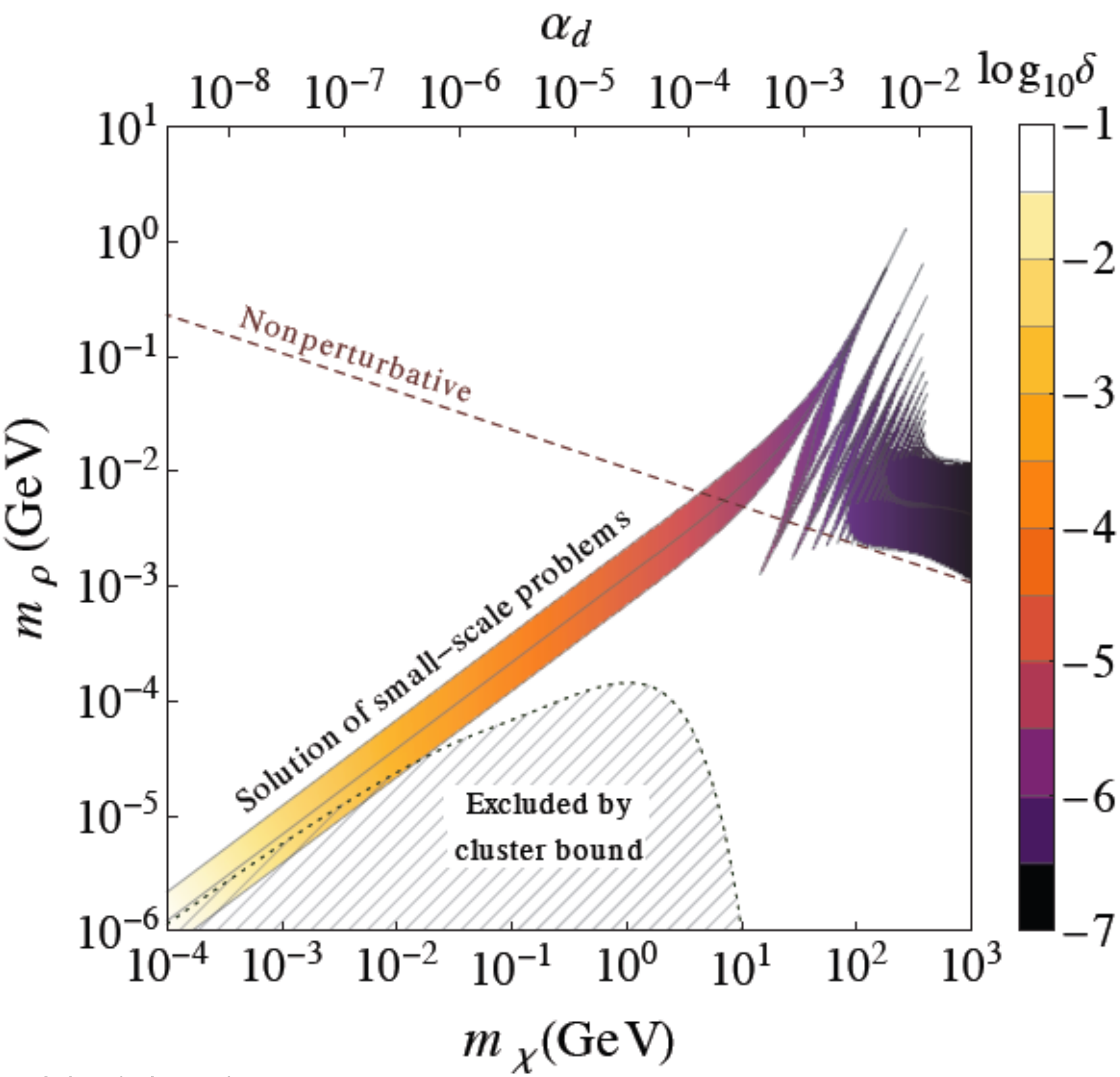
DM-DR Scattering

$$\sigma_{\eta\chi_-} = \frac{8\pi\alpha_{\rm d}^2\omega^4}{\Delta m_\chi^6}\left(1 + \frac{16\Delta m_\chi^2}{3m_\rho^2} + \frac{8\Delta m_\chi^4}{m_\rho^4}\right)$$

$$T_{\rm kd} \simeq 0.5\,{\rm keV}\frac{\delta}{10^{-4.5}}\left(\frac{m_\chi}{\rm GeV}\right)^{7/6}\left(\frac{10^{-4}}{\alpha_{\rm d}}\right)^{1/3}\xi_{\rm kd}^{-4/3}$$

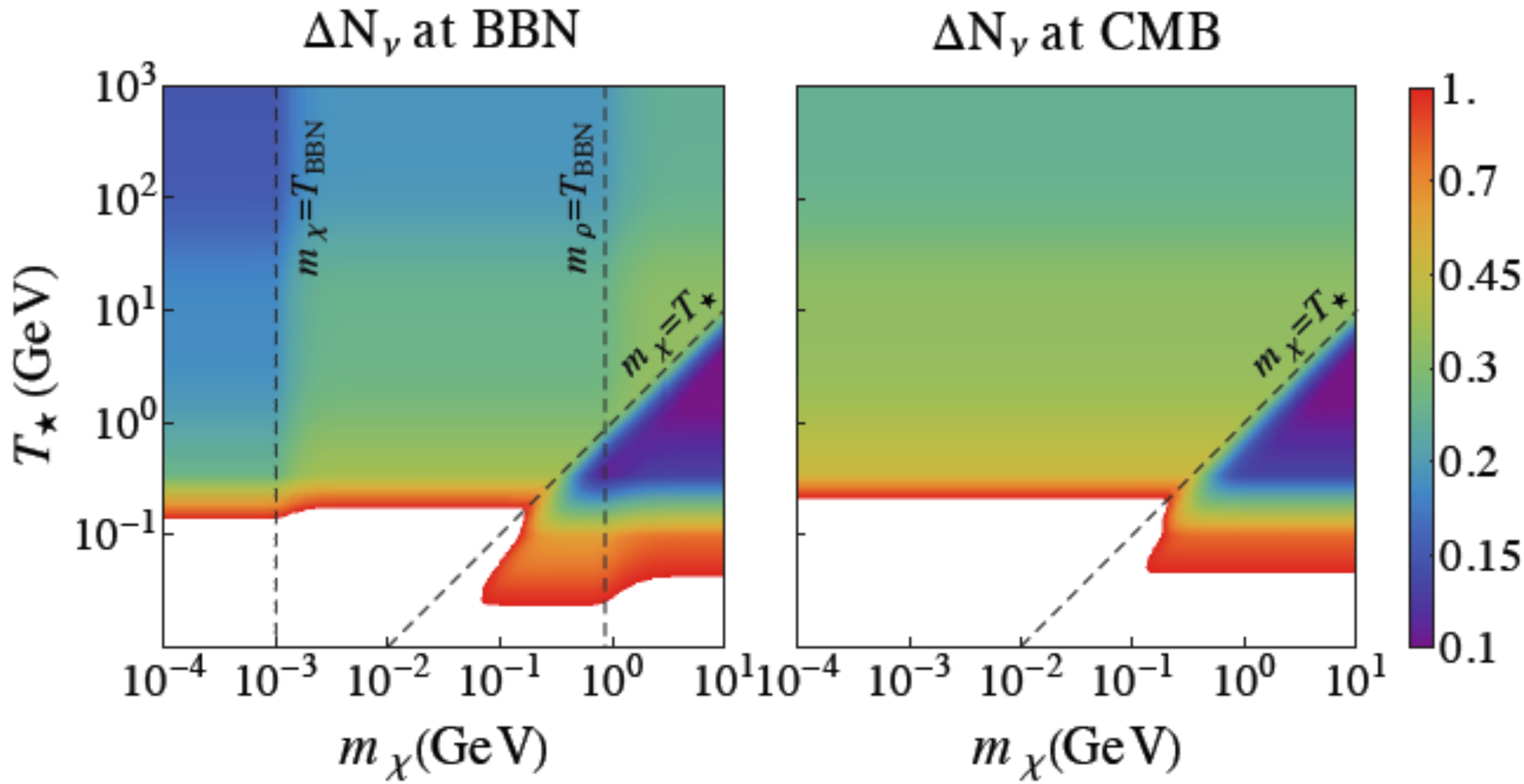
Chu and Dasgupta (2014)

Solving Small-Scale Problems



Chu and Dasgupta, 2014 (PRL)

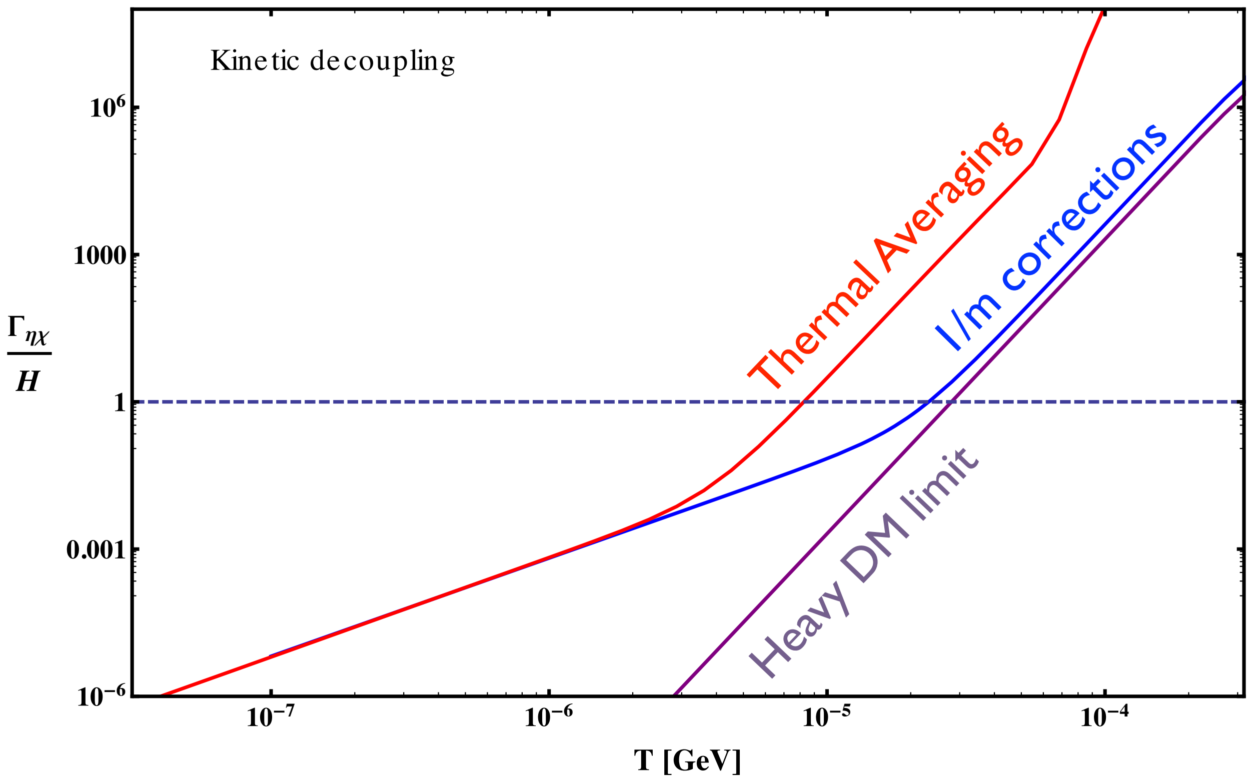
Dark Radiation Predictions



Chu and Dasgupta, 2014 (PRL)

dNeff > 0.1 is detectable using EUCLID, via lensing of the CMB

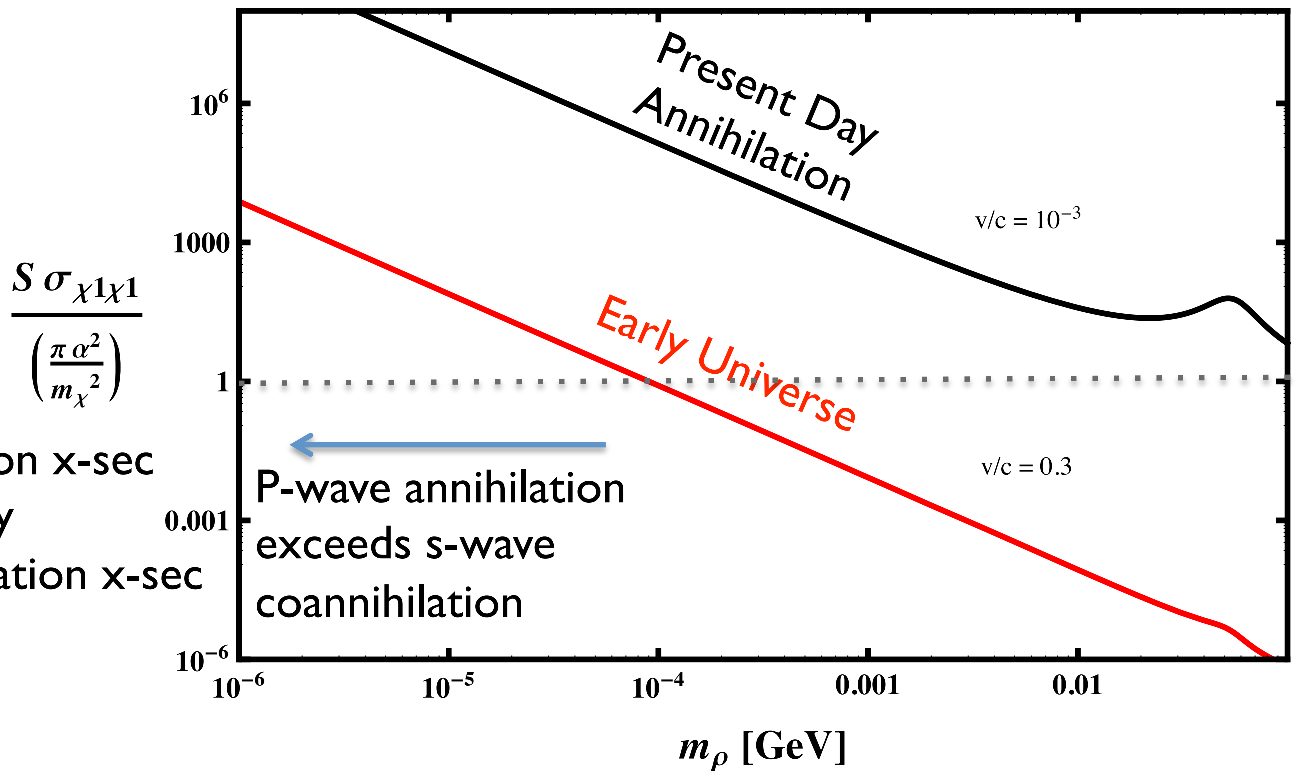
Kinetic Decoupling Revisited



Our previous result ignored some small correction suppressed by m_DM and crudely treated the thermal averaging. These corrections lead to further delaying of kinetic decoupling

Das and Dasgupta (to appear)

Sommerfeld Enhancement



Annihilation x-sec Divided by Coannihilation x-sec

P-wave suppressed DM annihilation is hugely enhanced by Sommerfeld effects at late times. This can even become the dominant annihilation channel even at early times (exceeding the s-wave coannihilation rate) and at late times!

Das and Dasgupta (to appear)

Summary and Outlook

Solution of the missing satellites problem using particle physics is possible with DM-DR interactions. These can be included in models which have DM-DM interaction

Using neutrinos as the radiation bath is getting constrained, as there are tensions with BBN, CMB, oscillation expts. etc.

Using a Goldstone boson of a same symmetry that gives DM self-interaction remains attractive. Finite-T and Sommerfeld corrections are very important. Indirect detection may become possible at late times!

Acknowledgements

My sincere thanks to

Kai Schmidt-Hoberg, who agreed to present some of these results after I had to cancel my visit owing to visa troubles at the last minute. Of course, all responsibility for errors lies with me!

The organizers, esp. Torsten and Joern, for smoothly taking care of everything.

My collaborators on these ideas – Xiaoyong Chu (ICTP), Joachim Kopp (Mainz), and Anirban Das (TIFR).