Dark Matter-Neutrino Coupling, or on the Structure Function of Dark Matter

David McKeen
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INT Nuclear Aspects of DM Searches Workshop
Dec. 11, 2014

Based on:
Bridget Bertoni, Seyda Ipek, DM, & Ann Nelson, 1412.3113

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$$\left(Q \sim \frac{1}{10\ \mathrm{kpc}} \sim 10^{-33}\ \mathrm{MeV}\right)$$

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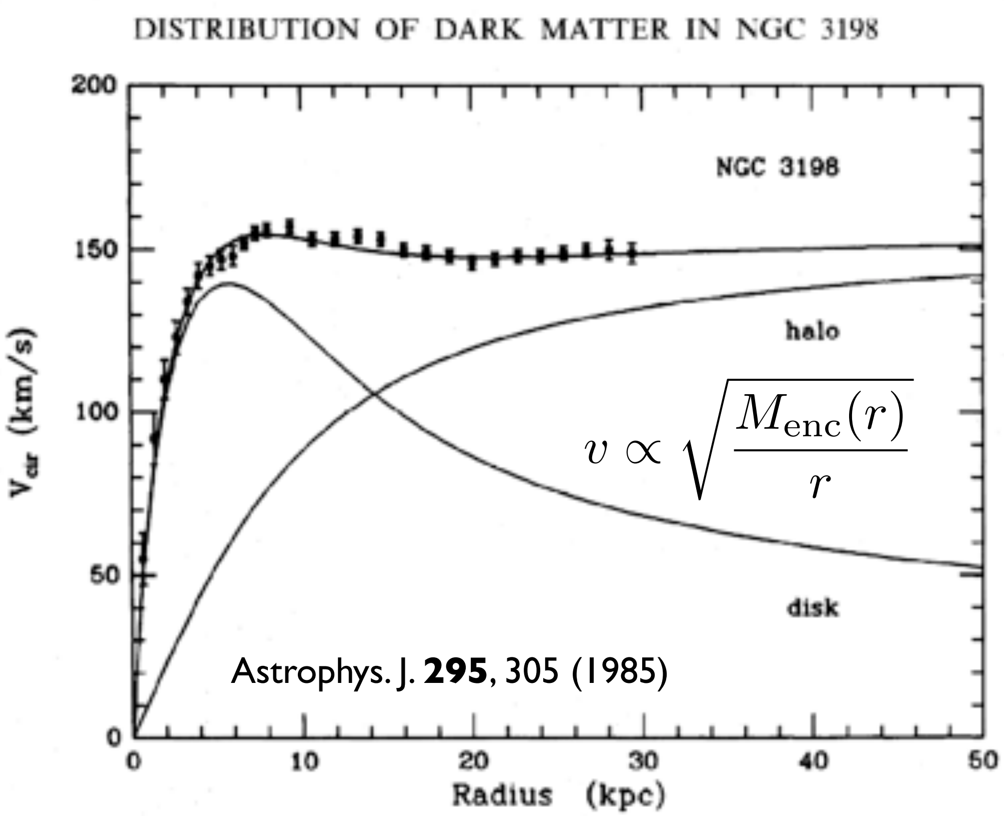
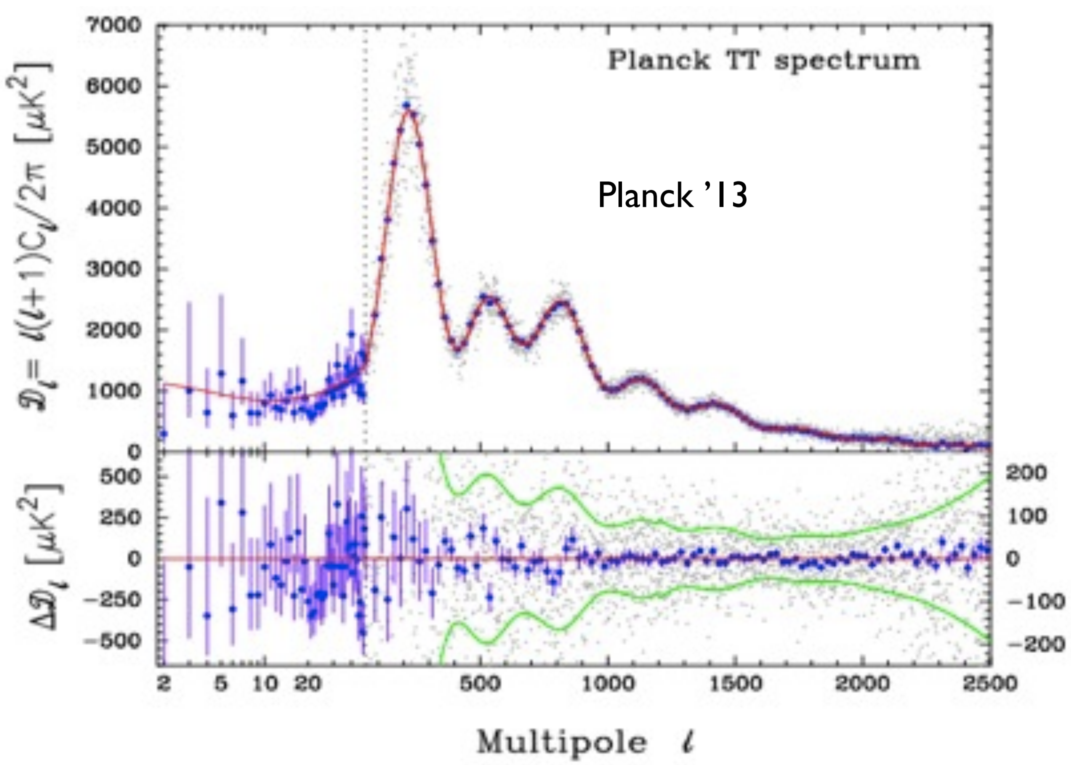
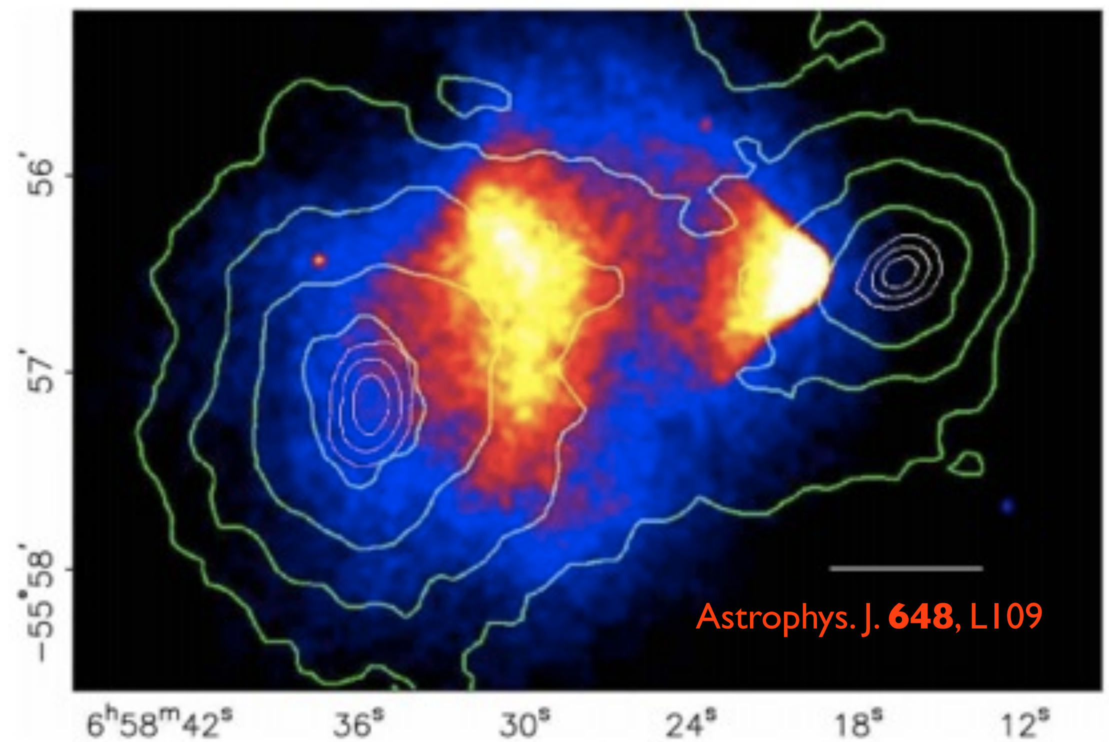
Outline

- Lightning review of DM & structure formation
- Physics that sets the scales of DM halos
- What we know about the sizes of the smallest halos. Problems?
- Could interactions between DM and neutrinos fix such problems?
- What would a model that does this look like? What are its implications?

Why Dark Matter?





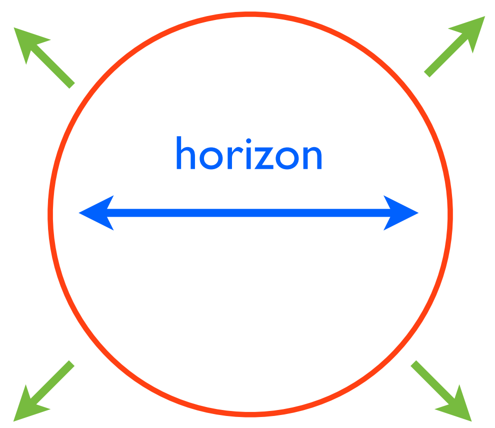


$$\Omega_d \sim 0.2$$

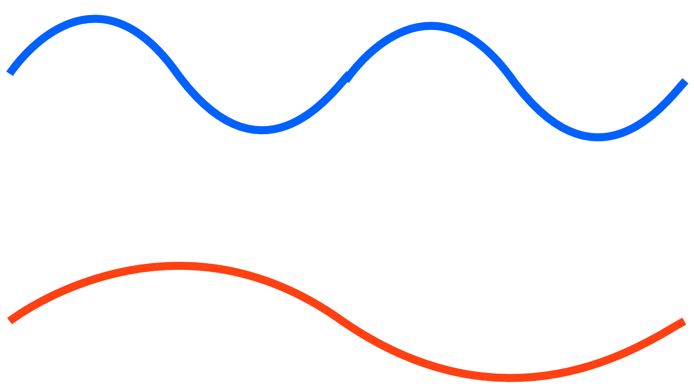
$$\Omega_b \sim 0.04$$

Structure Formation

We live in an expanding and cooling universe after a period of inflation



Perturbations on smaller scales enter the horizon earlier, when it was hotter



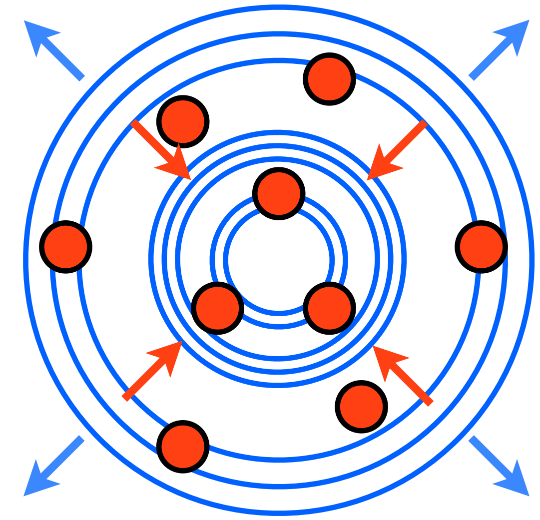
⇒hierarchical DM clustering:

small scale structures form earlier

Roughly, gravity vs. pressure compete

Acoustic Oscillations

Before DM is decoupled, it "feels" pressure due to relativistic fluid



$$H_{\rm d}^{-1} = a_{\rm d}\eta_{\rm d}, \;\; \eta_{\rm d} = \int_0^{t_{\rm d}} \frac{dt}{a(t)}$$

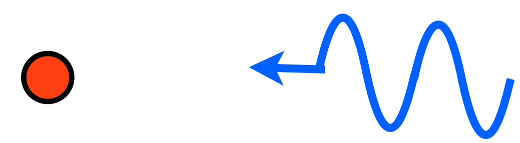
This damps structure on scales smaller than the horizon at decoupling

$$M_{\rm ao} = \rho_\chi(T_{\rm d}) \frac{4\pi}{3} (a_{\rm d}\eta_{\rm d})^3 = 2 \times 10^8 M_\odot \; \left(\frac{g_{\rm eff}(T_{\rm d})}{3.36}\right)^{-1/2} \left(\frac{T_{\rm d}}{\rm keV}\right)^{-3}$$

Kinetic Decoupling

DM sitting in relativistic fluid
(provides the pressure)

$$p_r \sim T$$



$$p_{\rm DM} \sim \sqrt{m_{\rm DM} T}$$

Change in DM momentum
after *N* collisions O(1)

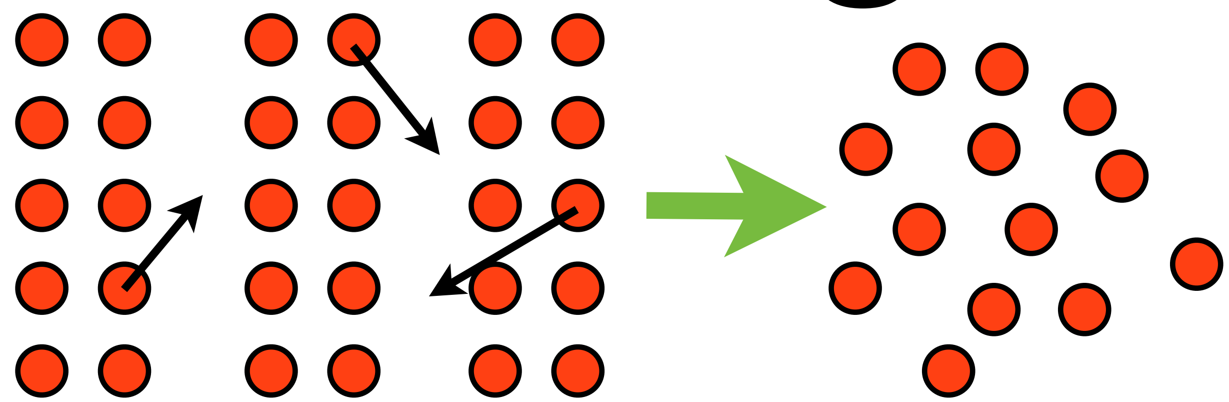
$$\Delta p_{\rm tot} \sim \sqrt{N} T \sim p_{\rm DM}$$
$$\Rightarrow N \sim \frac{m_{\rm DM}}{T}$$

Equilibrium maintained so long as $\displaystyle \frac{n_r \sigma}{N} \sim \frac{T}{m_{\rm DM}} n_r \sigma > H$

Temperature at decoupling estimated:

$$\sigma = \frac{T^2}{\Lambda^4}, \;\; H \propto \frac{T^2}{M_{\rm Pl}} \Rightarrow T_{\rm d} \sim \left(\frac{\Lambda^4 m_\chi}{M_{\rm Pl}} \right)^{1/4}$$

DM Free Streaming



After decoupling, DM free streams washing out structure on scales smaller than

$$\ell_{\rm eq} = \pi a_{\rm eq} \int_{t_{\rm d}}^{t_{\rm eq}} dt \frac{v_{\rm phys}}{a(t)}, \;\; v_{\rm phys} = v/a(t)$$

$$M_{\rm fs} = \rho_\chi(T_0) \frac{4\pi}{3} \ell_0^3$$
$$= 3 \times 10^5 M_\odot \left(\frac{g_{\rm eff}(T_{\rm d})}{3.36}\right)^{-1/2} \left(\frac{m_\chi}{10 \text{ MeV}}\right)^{-3/2} \left(\frac{T_{\rm d}}{\rm keV}\right)^{-3/2} \left\{1 + \ln\left[\left(\frac{g_{\rm eff}(T_{\rm d})}{3.36}\right)\left(\frac{T_{\rm d}}{\rm keV}\right)\right]/6.0\right\}^3 .$$

Smallest DM Objects

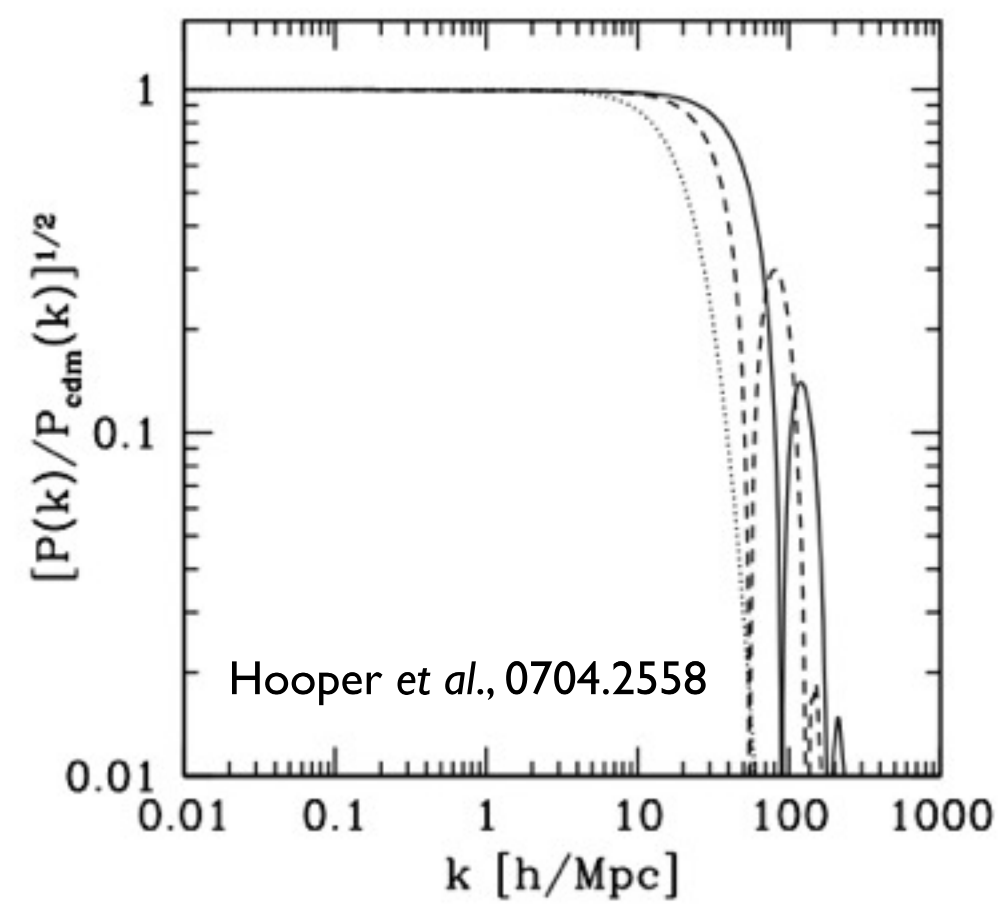
Smallest possible DM halos have masses ~larger of M_{ao} or M_{fs}

$$\frac{M_{\rm fs}}{M_{\rm ao}} = 1.5 \times 10^{-3} \left(\frac{m_\chi}{10\ {\rm MeV}}\right)^{-3/2} \left(\frac{T_{\rm d}}{\rm keV}\right)^{3/2} \left\{1 + \ln\left[\left(\frac{g_{\rm eff}(T_{\rm d})}{3.36}\right)\left(\frac{T_{\rm d}}{\rm keV}\right)\right]/6.0\right\}^3.$$

For $T_{\rm d} \lesssim 100\ {\rm keV} \left(\frac{m_\chi}{10\ {\rm MeV}}\right)$

M_{ao} dominates

$$\Rightarrow M_{\rm cut} = M_{\rm ao} = 2 \times 10^8 M_\odot \left(\frac{g_{\rm eff}(T_{\rm d})}{3.36}\right)^{-1/2} \left(\frac{T_{\rm d}}{\rm keV}\right)^{-3}$$



Vanilla WIMP Scales

For a DM-SM scattering cross section of

$$\sigma \sim \frac{T^2}{\Lambda^4}, \ \Lambda \sim 100 \text{ GeV}$$

the decoupling temperature is

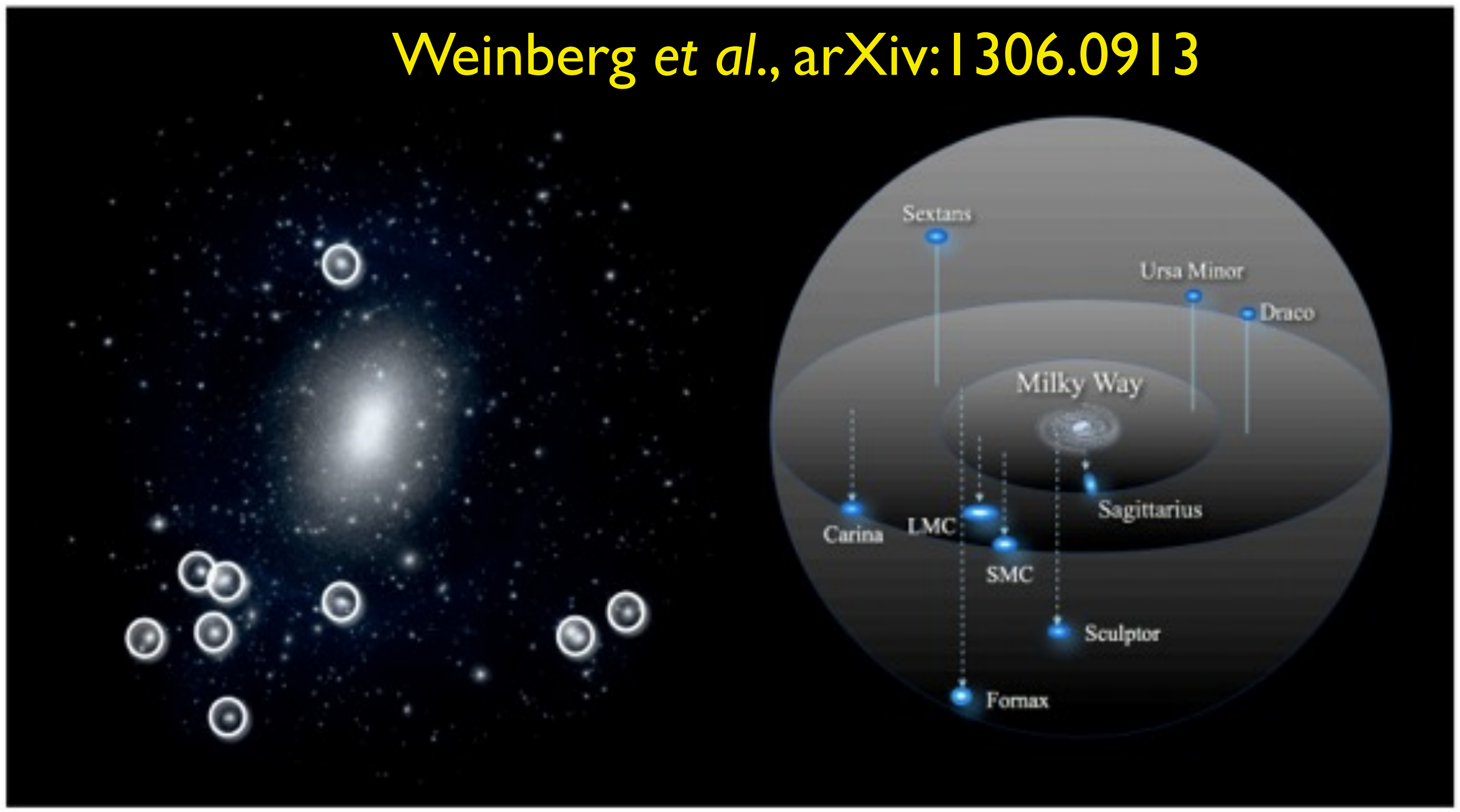
$$T_\mathrm{d} = \left(\frac{\Lambda^4 m_\chi}{M_\mathrm{Pl}}\right)^{1/4} = 10 \text{ MeV} \left(\frac{\Lambda}{100 \text{ GeV}}\right) \left(\frac{m_\chi}{100 \text{ GeV}}\right)^{1/4}$$

This results in a cut off mass of

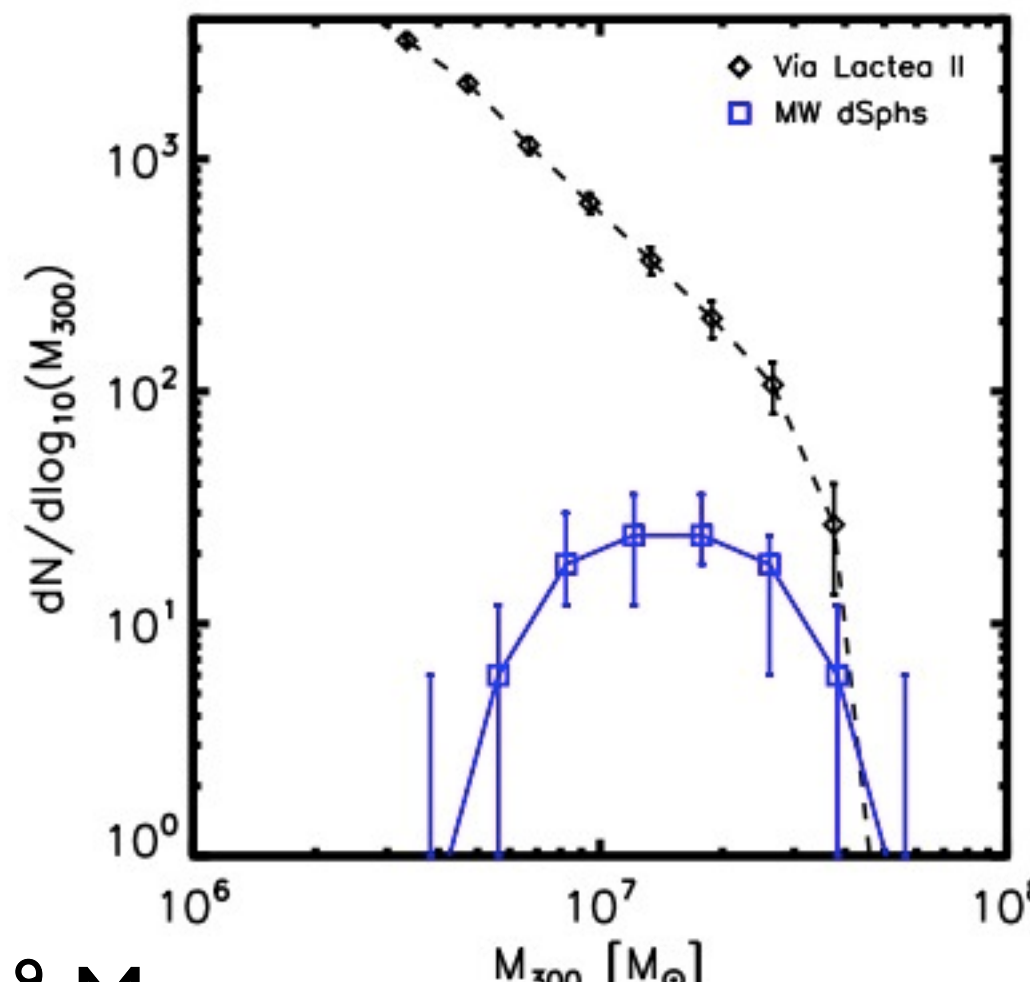
$$M_\mathrm{cut} \sim 10^{-4} M_\odot$$

What does the data say?

Missing Satellites



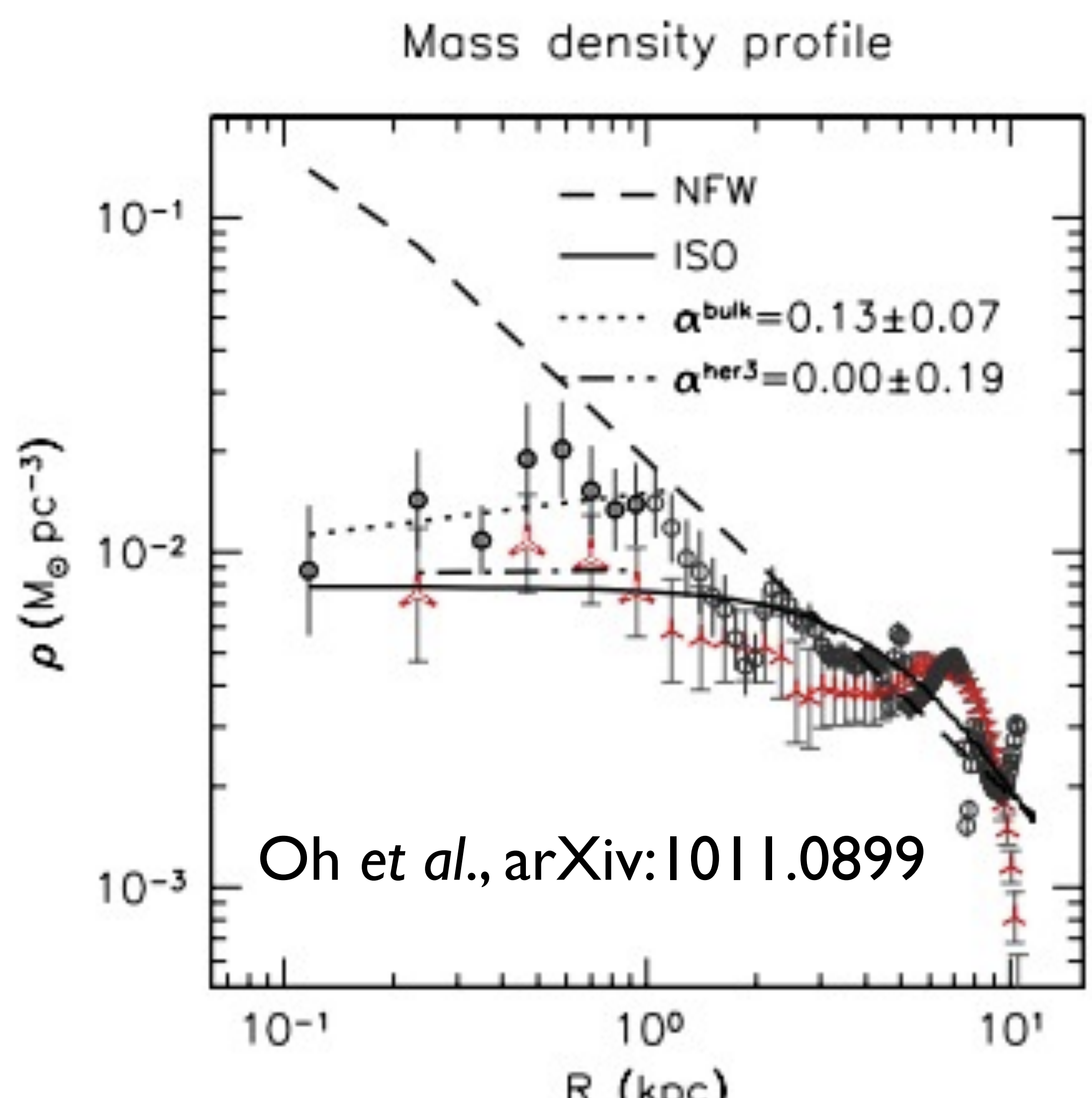
Bullock, arXiv:1009.4505



Compared to expectation, fewer small halos orbiting Milky Way

Suggestive of a cut off ~$10^{7\text{-}9}$ $M_\odot$

"Too Big to Fail" & Core vs. Cusp



N-body simulations indicate that most massive MW satellites more massive than those we know, large enough to form stars

DM density profiles appear less cuspy than NFW

$$\rho_{\rm NFW}(r) = \frac{\rho_H}{r/R_H(1+r/R_H)^2}$$

Potential Resolutions

Could be fixed by baryonic effects

DM could be "warm"

DM could self-interact

DM could stay in kinetic equilibrium with the plasma longer...

Shoemaker, 1305.1936
van den Aarssen et al., 1205.5809
...

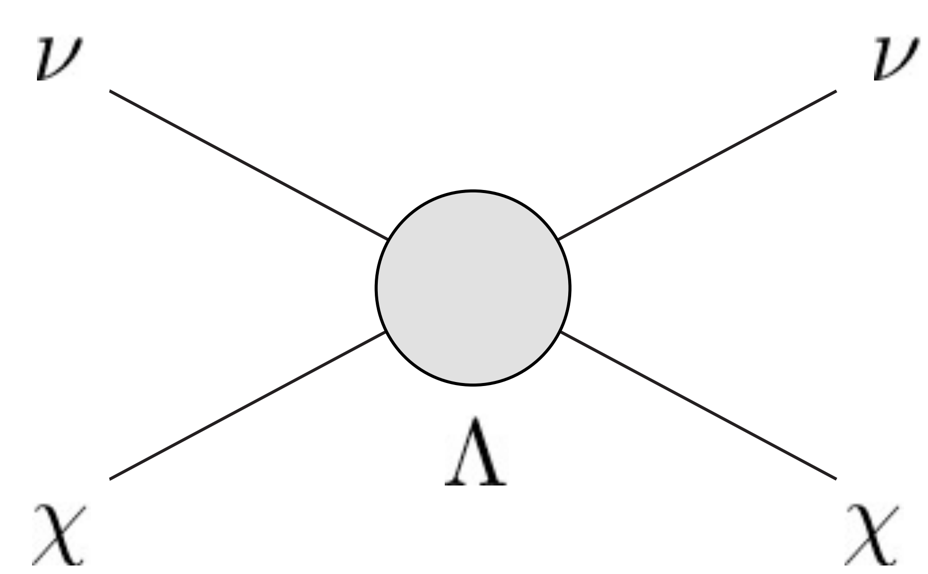
Coupling to Neutrinos?

Recall $M_{\rm ao} = 2 \times 10^8 M_\odot \left(\frac{T_{\rm d}}{\rm keV}\right)^{-3}$

Neutrinos are another form of radiation

Want $T_{\rm d} \sim {\rm keV}$

So if $\sigma \sim \frac{T^2}{\Lambda^4},\ T_{\rm d} \sim \left(\frac{\Lambda^4 m_\chi}{M_{\rm Pl}}\right)^{1/4}$



$$\Rightarrow \Lambda^4 m_\chi = (10 - 100\ {\rm MeV})^5$$

$\sigma_{\rm ann} v \gg 3 \times 10^{-26}\ \frac{\rm cm^3}{\rm s}$ ⇒Asymmetric DM

What would a model of this look like?

Model Building

Safe to couple through the "neutrino portal" LH

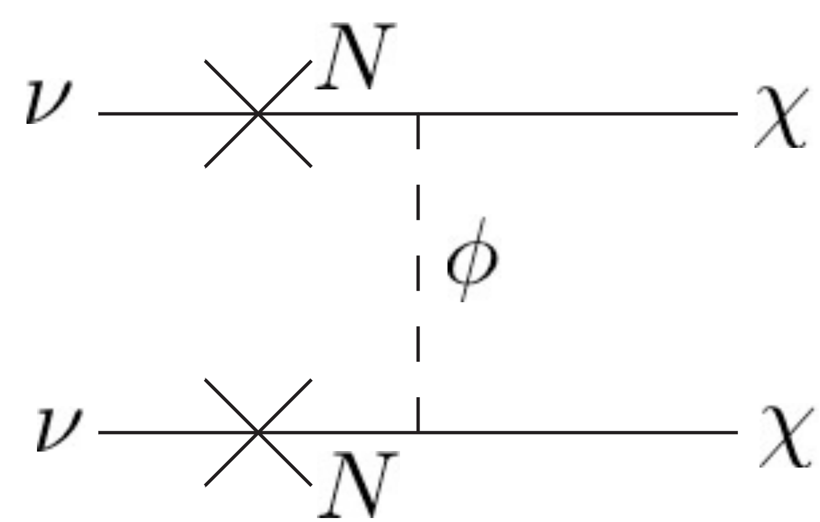
But an operator like $LH\chi$ would lead to DM decay

Need a higher dimensional operator $\frac{1}{\Lambda}LH\phi\chi$

Add a sterile neutrino

$$\mathcal{L}_{\rm m} = -MNN + \lambda_i NHL_i + \text{h.c.}$$

$$\mathcal{L}_{\rm int} = -y_1\phi^* N\chi_L + \text{h.c.}$$



Model Building

We get a cross section $\sigma = \frac{g^4 T^2}{8\pi m_\phi^4}, \; g = y \sin\theta$

with a mixing angle $\theta \simeq \sqrt{\frac{m_\nu}{M}}$

we need $\Lambda \sim \frac{m_\phi}{g}, m_\chi \sim \mathcal{O}(\text{10s of MeV})$

g (i.e. θ) can't be tiny⇒*N* is quite light (< few eV)

Not good!

Model Building

Two sterile neutrinos with opposite lepton number

$$\mathcal{L}_{\rm m} = -m_{ij}\nu_i\nu_j - MN_1N_2 + \lambda_i N_1 H L_i + {\rm h.c.}$$

lepton number conserved in sterile neutrino interactions

EWSB $\Rightarrow \begin{pmatrix} m_{ij} & \lambda_j v & 0 \\ \lambda_i v & 0 & M \\ 0 & M & 0 \end{pmatrix}$

$$-\mathcal{L}_{\rm int} = (y_1\phi^* N_1 + y_2\phi N_2)\,\chi_L + {\rm h.c.}$$

$$\nu_i = U_{ij}\hat{\nu}_j$$

$$i = e, \mu, \tau, N, \quad j = 1, \ldots, 4$$

mixing angle decoupled from neutrino mass: 3 light, 1 heavy

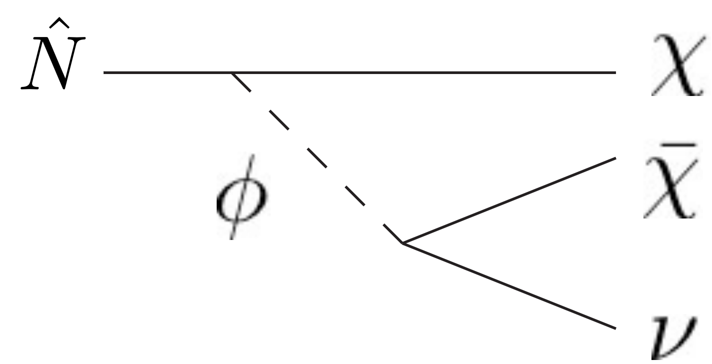
$$g \equiv y_2\sqrt{|U_{e4}|^2 + |U_{\mu 4}|^2 + |U_{\tau 4}|^2}$$

$$\sigma_{\nu\chi} = \sum_{i=1}^{3}\sigma_{\hat{\nu}_i\chi} = \frac{g^4}{8\pi}\frac{E_\nu^2}{\left(m_\phi^2 - m_\chi^2\right)^2} = 8\times 10^{-38}{\rm cm}^2\left(\frac{g}{0.3}\right)^4\left(\frac{E_\nu}{1\ {\rm keV}}\right)^2\left(\frac{35\ {\rm MeV}}{\sqrt{m_\phi^2 - m_\chi^2}}\right)^4$$

The Model

Heavy neutrino is Dirac $\hat{N} = \begin{pmatrix} \hat{\nu}_4 = c_\theta N_2 + s_\theta \nu_\tau \\ N_1^* \end{pmatrix}$

decays invisibly

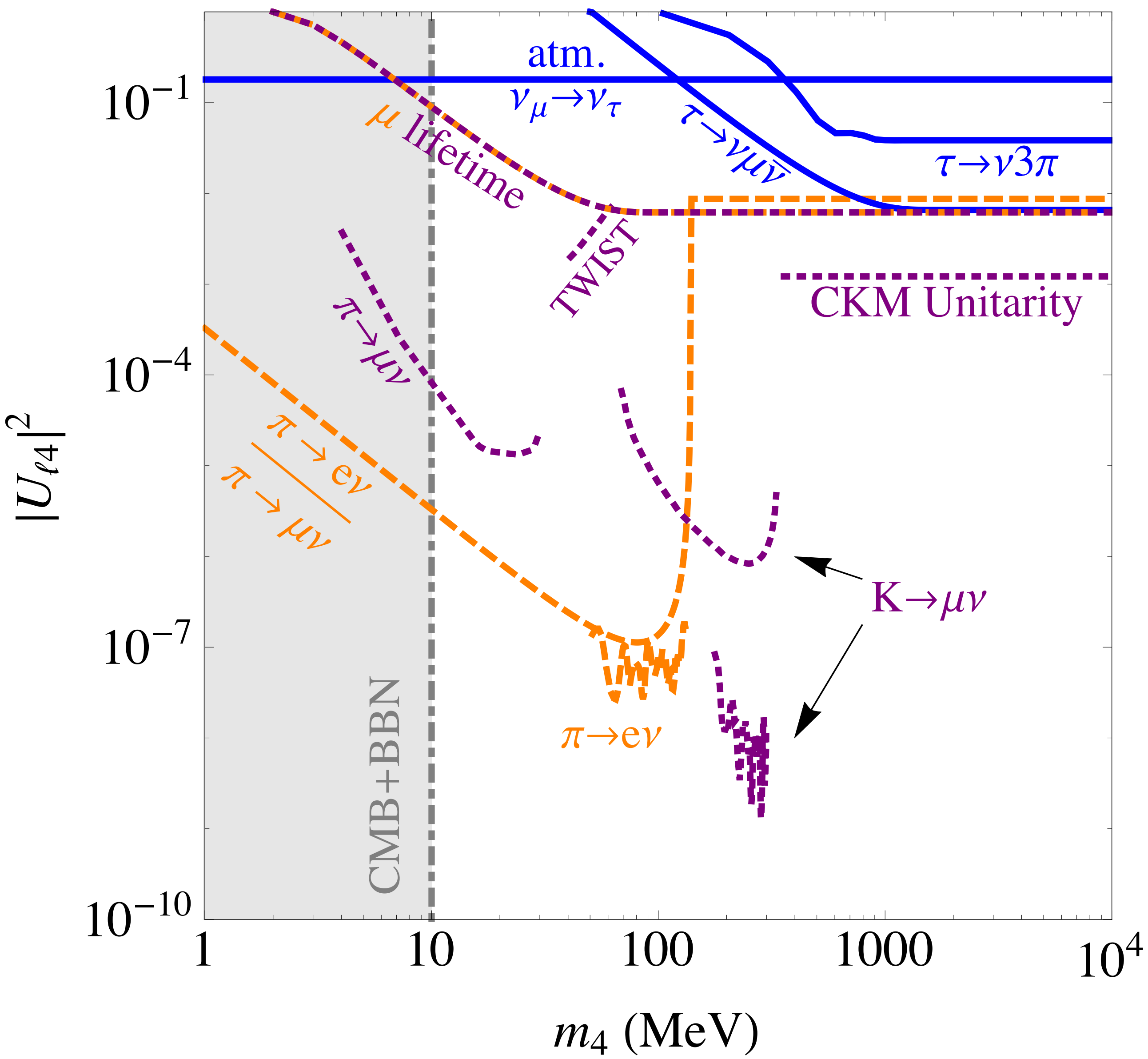


$$\Gamma_{\hat{N}\to\nu\chi\bar{\chi}} = \frac{\left(y_1^2 + y_2^2 c_\theta^2\right) m_4}{32\pi} \simeq 3\ \text{MeV} \left(\frac{m_4}{300\ \text{MeV}}\right)$$

visible decays are G_F suppressed

$$\Gamma_{\hat{N}\to\nu e^+ e^-} = \frac{s_\theta^2 G_F^2 m_4^5}{192\pi^3} \simeq 5 \times 10^{-15}\ \text{MeV} \left(\frac{s_\theta}{0.3}\right)^2 \left(\frac{m_4}{300\ \text{MeV}}\right)^5$$

What parameter values do we need?



Require:

$$\Lambda \sim \frac{\sqrt{m_\phi^2 - m_\chi^2}}{\sqrt{|U_{e4}|^2 + |U_{\mu 4}|^2 + |U_{\tau 4}|^2}} \sim \mathcal{O}(10\text{s of MeV})$$

⇒couple to the

τ neutrino

Neutrino Oscillations

can decompose mixing matrix as

$$U = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c_\theta & s_\theta \\ 0 & 0 & -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{23} & s_{23} & 0 \\ 0 & -s_{23} & c_{23} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} & 0 \\ 0 & 1 & 0 & 0 \\ -s_{13} & 0 & c_{13} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 & 0 \\ -s_{12} & c_{12} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13} & 0 \\ -c_{23}s_{12} - c_{12}s_{13}s_{23} & c_{12}c_{23} - s_{12}s_{13}s_{23} & c_{13}s_{23} & 0 \\ -c_\theta\left(c_{12}c_{23}s_{13} - s_{12}s_{23}\right) & -c_\theta\left(c_{23}s_{12}s_{13} + c_{12}s_{23}\right) & c_\theta c_{13}c_{23} & s_\theta \\ s_\theta\left(c_{12}c_{23}s_{13} - s_{12}s_{23}\right) & s_\theta\left(c_{23}s_{12}s_{13} + c_{12}s_{23}\right) & -s_\theta c_{13}c_{23} & c_\theta \end{pmatrix}$$

U_{e3}: Daya Bay, unaffected by θ_τ given by θ_{13}

$U_{\mu 3}$: K2K and MINOS, unaffected by θ_τ given by θ_{23}

U_{e2}: Kamland, unaffected by θ_τ given by θ_{12}

Solar neutrino flux sensitive to θ_τ, θ_{12}: $\sin\theta_\tau < 0.6$

Super-K Atmospheric: $\sin\theta_\tau < 0.4$ $\quad \nu_e, \nu_\mu, c_\theta \nu_\tau - s_\theta N_2$

Supernovae

Neutrinos produced in SN at T~30 MeV

Initial neutronization burst of ν_e

DM light enough to be produced but doesn't contribute to cooling, thermal dist. with neutrinos to large radii

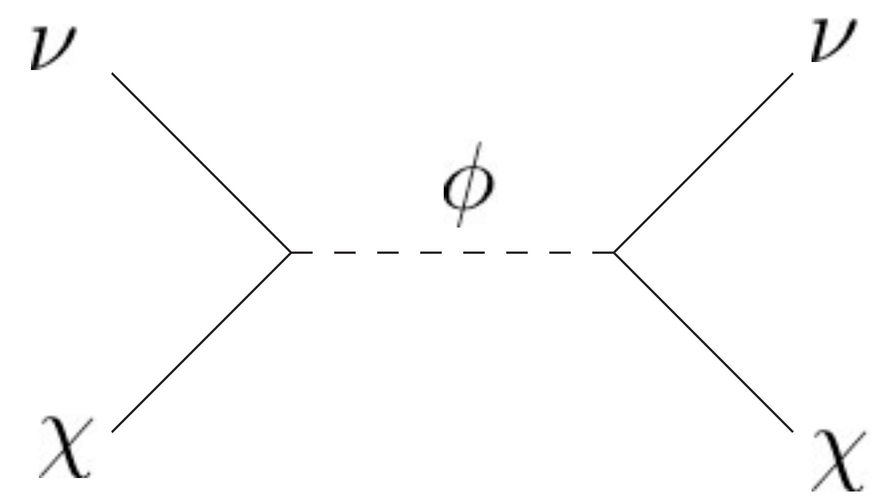
Neutrinos free stream when density is low, T~5 MeV: DM production suppressed, similar to strong ν self-interactions

Fayet, Hooper, & Sigl, hep-ph/0602169 find $m_\chi > 10~\mathrm{MeV}$

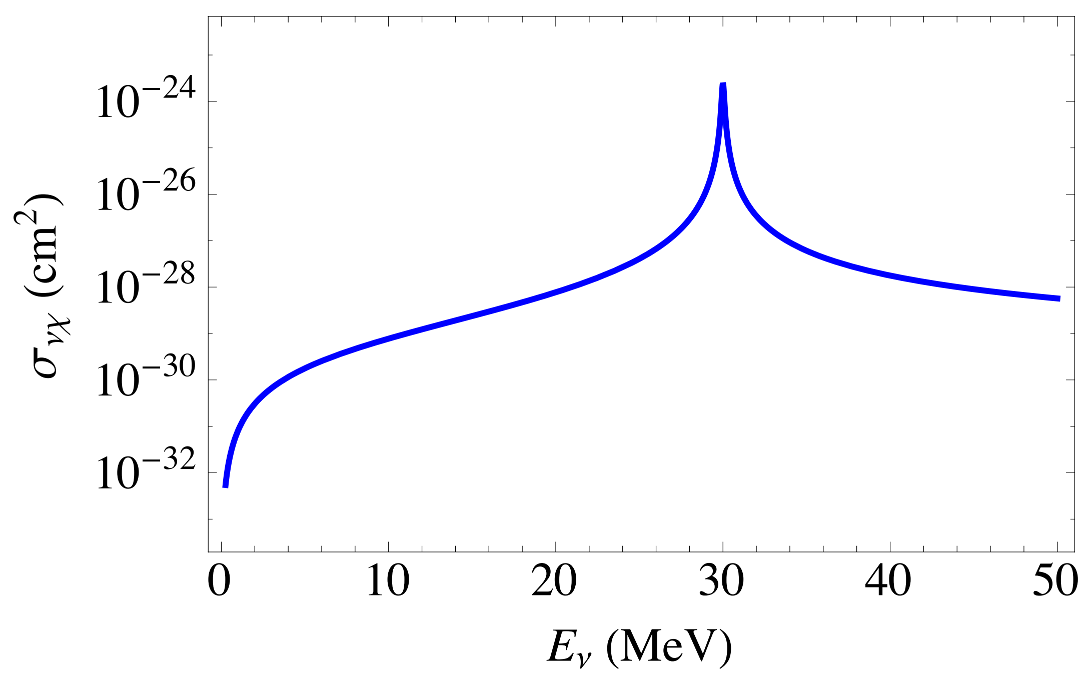
Mangano et al., hep-ph/0606190 & Boehm et al., 1303.6270: $\sigma_{\hat{\nu}_i \chi} \lesssim 10^{-25}~\mathrm{cm}^2 \left(\frac{m_\chi}{\mathrm{MeV}}\right)$

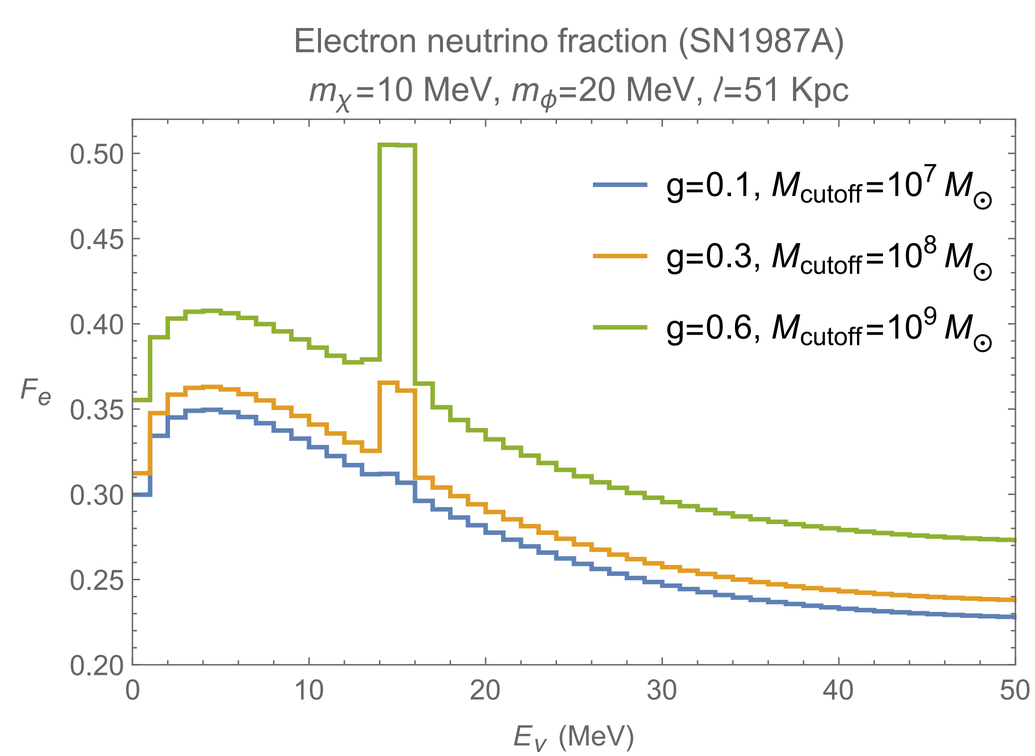
Neutrinos from SN

MeV energy neutrinos
from SN scatter on DM



Resonance at $E_\nu = \dfrac{m_\phi^2 - m_\chi^2}{2m_\chi}$ can be in the right range



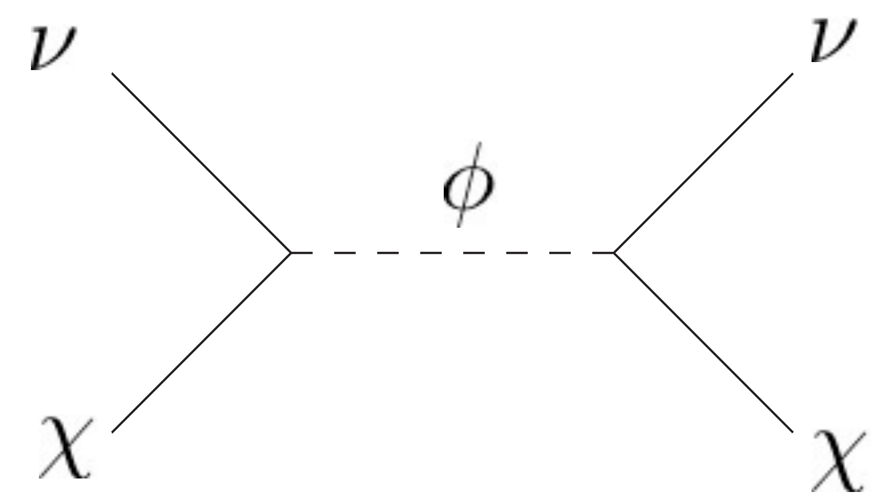


$\mathrm{Flux}_i \propto e^{-\Gamma_i d}$ $\quad \Gamma = \sigma_{\nu\chi} \times \dfrac{1}{d} \displaystyle\int dx\, n_\chi$

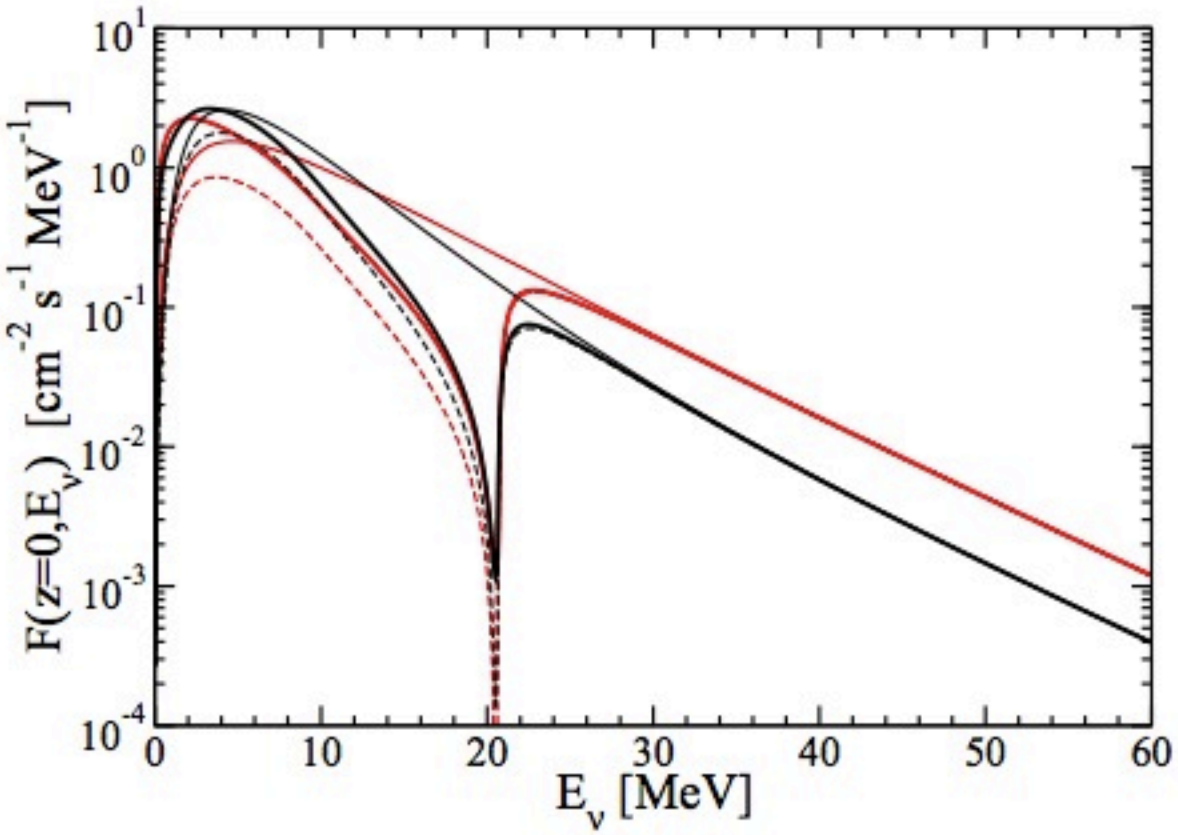
$\dfrac{1}{\Gamma_1} \simeq \dfrac{6}{\Gamma}, \quad \dfrac{1}{\Gamma_2} \simeq \dfrac{3}{\Gamma}, \quad \dfrac{1}{\Gamma_3} \simeq \dfrac{2}{\Gamma}$

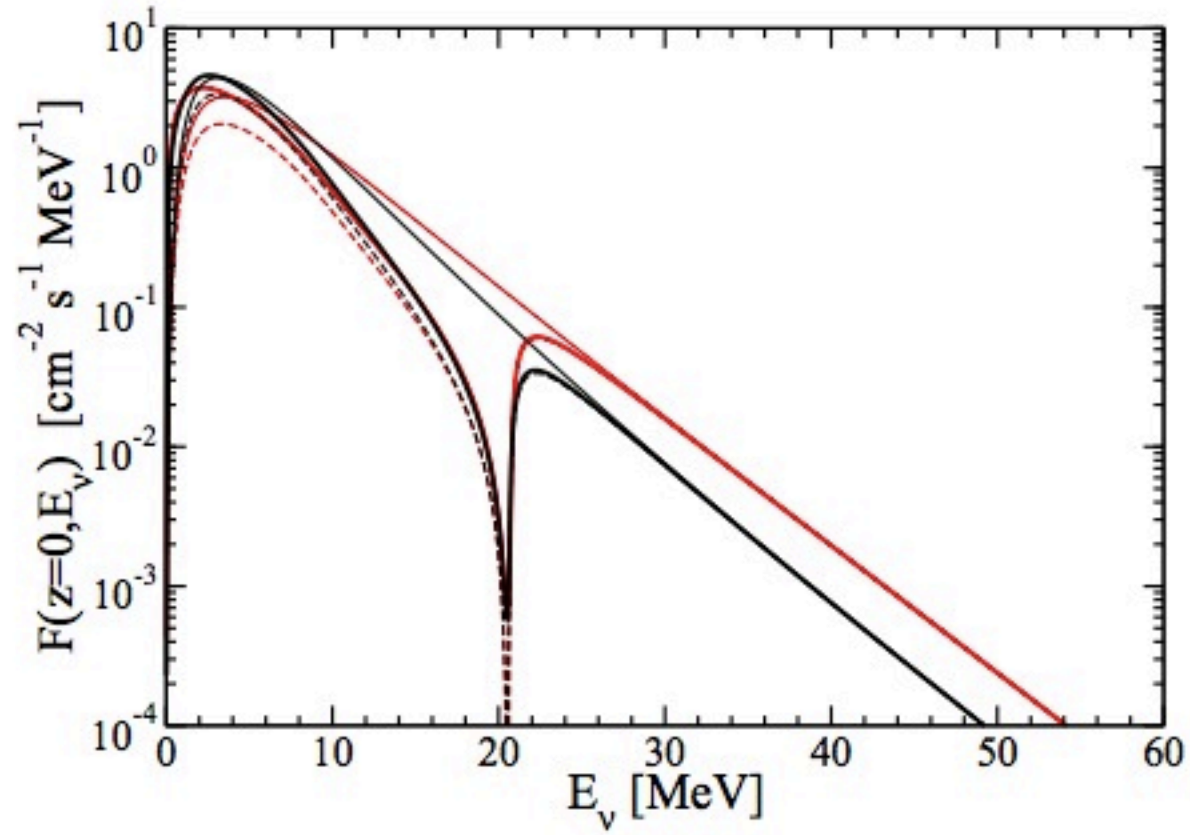
DSNB

Same process as for nearby SN



Farzan & Palomares-Ruiz 1401.7019





Potentially visible at Hyper-K

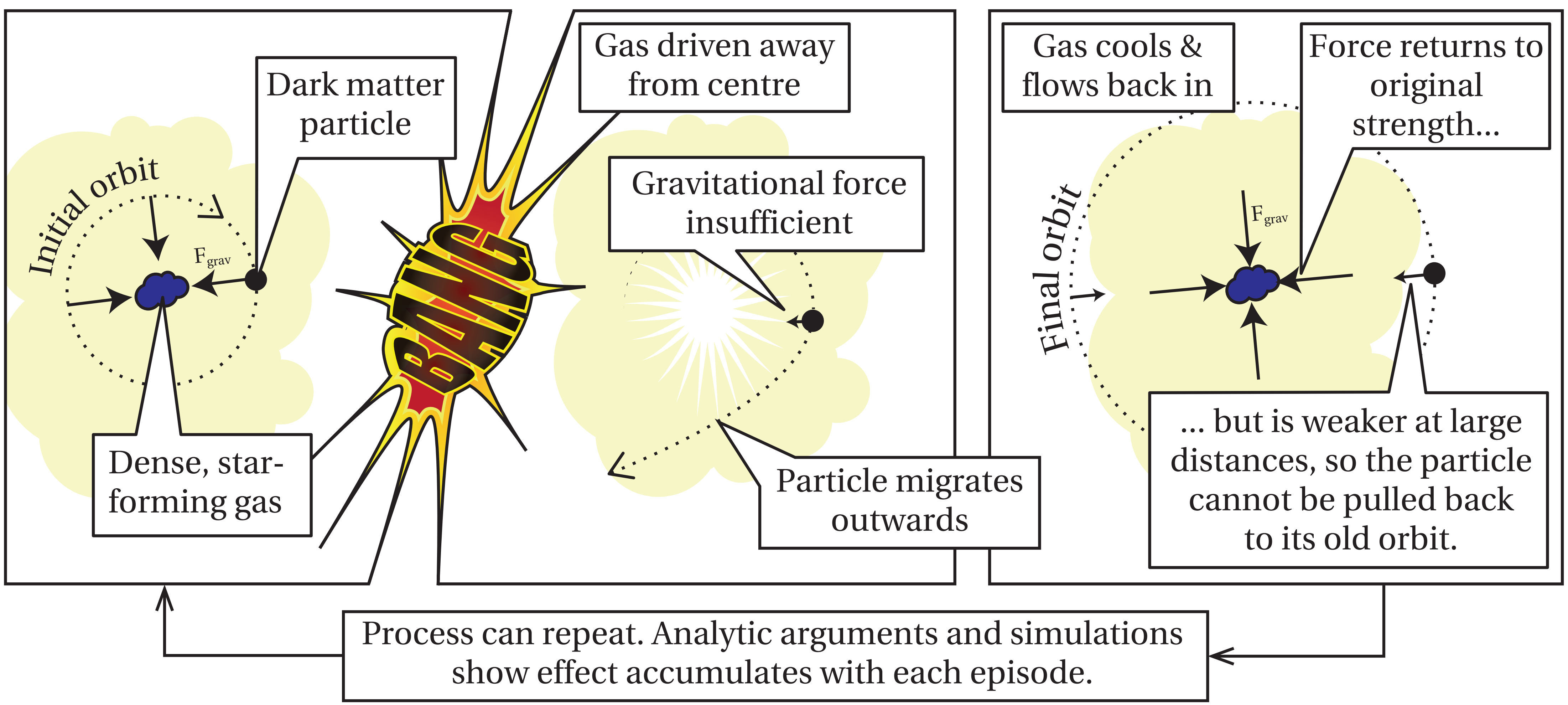
Neutrinos from SN: Core vs. Cusp?

Feedback from baryons could be a possible sol'n for cuspy halo problem

$$10^{51}\ \text{ergs} \times \epsilon_{SN}$$

transferred from SN to DM

$\epsilon_{SN} \sim 0.1 - 0.4$ an interesting value



Pontzen & Governato, 1402.1764

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10^{53} ergs $\times\ \epsilon_{\nu\chi}$

$$\epsilon_{\nu\chi} \sim \frac{1}{2} \times \frac{1}{3} \times \frac{1}{E_\nu} \int dE'_\nu \, (E_\nu - E'_\nu) \frac{d\sigma_{\nu\chi}}{dE'_\nu} \times \int d\ell \, n_\chi$$

Find $\epsilon_{\nu\chi} \sim 10^{-3}$ for $M_{\rm cut} = 10^9 M_\odot$

compare against

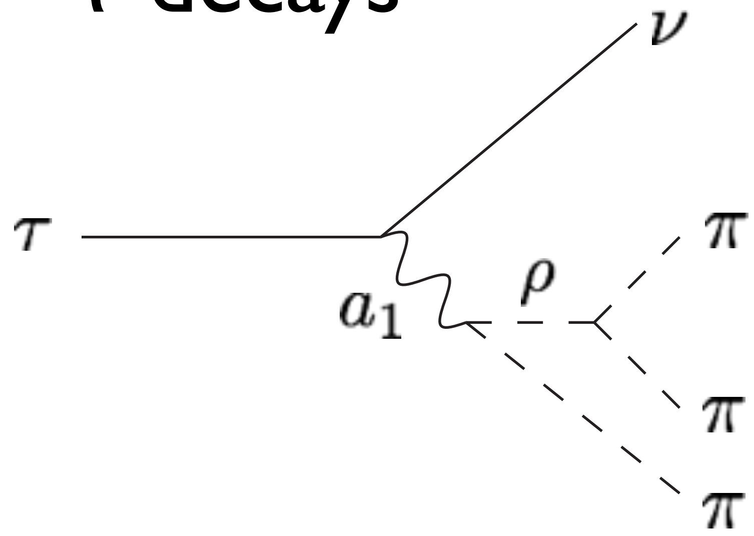
$\left[\rho(r) = \frac{1}{r} \to \text{const.}\right]$

$$\Delta W \sim \frac{1}{30} \frac{G M_{\rm enc}^2}{r_0} \sim 3 \times 10^{54} \text{ ergs} \left(\frac{M_{\rm enc}}{10^9 M_\odot}\right)^2 \left(\frac{r_0}{\rm kpc}\right)$$

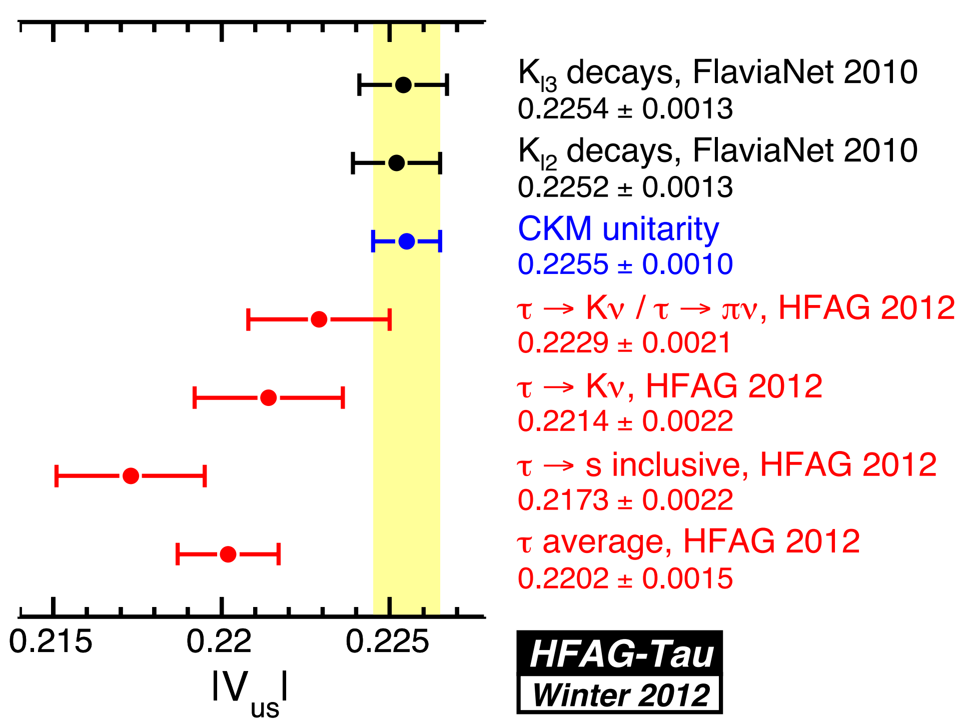
But this is deposited in a small fraction of the DM...

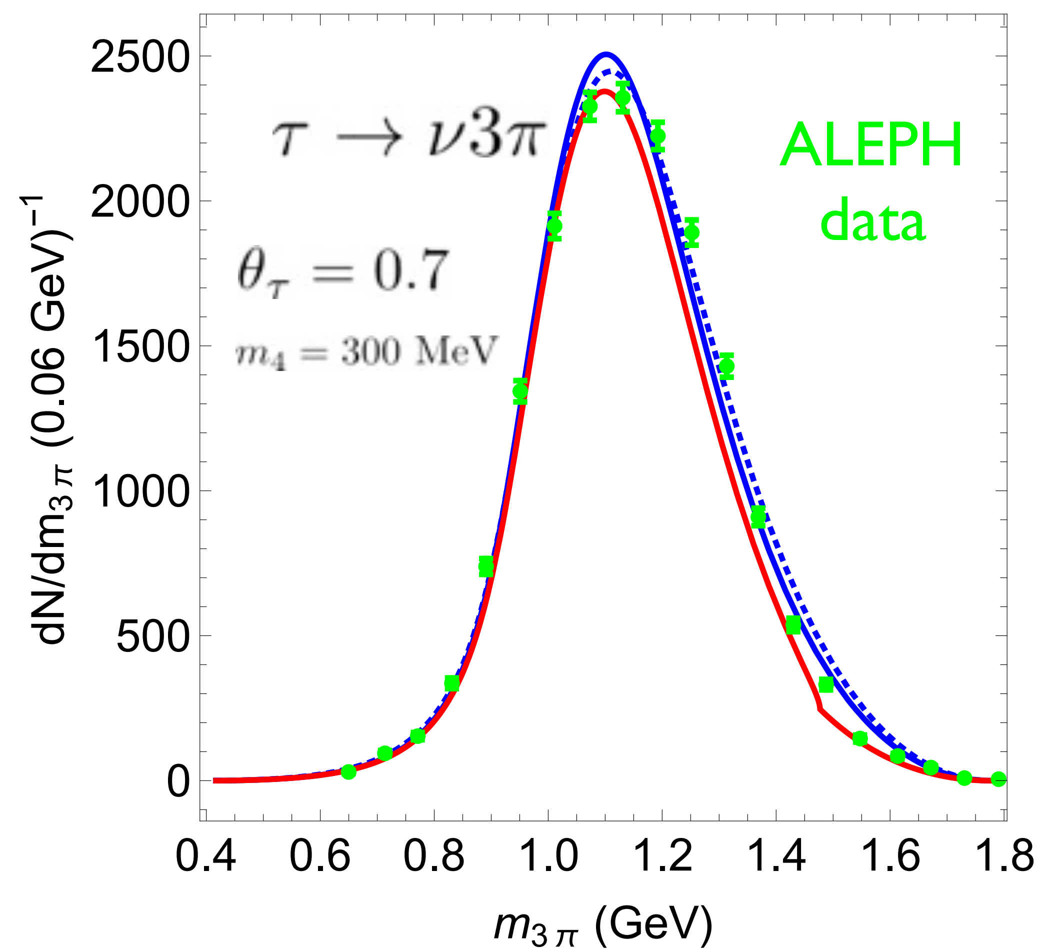
Future tests

τ decays



τ→K decays slightly low...





Super-K limit on $U_{\tau 4}$ is statistics limited

PINGU could provide factor of 1.5 improvement

Conclusions

- Possible sign of interesting departure from standard DM paradigm at small scales
- A large coupling of DM to neutrinos could help alleviate this
- A realistic model appears to require heavy neutrino in the 100 MeV-1 GeV range
- Heavy neutrino is mostly sterile with a small(ish) ν_τ admixture
- Implications for τ decays, SN observations