Title: Dark matter coupling with a sterile neutrino inhibits the birth of small scale structure: implications and tests

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Abstract: <p>Recent comparison between observation and expectation could point to problems with the standard cold, non-interacting dark matter picture, one of which being how small the smallest gravitationally bound dark matter halos are. I will review the cold dark matter picture and the experimental tests. One solution to the problems comes from coupling the dark matter to neutrinos. I will describe the model building requirements of such a coupling and determine how to test this scenario.</p>

# Dark matter coupling with a sterile neutrino inhibits the birth of small scale structure: implications and tests

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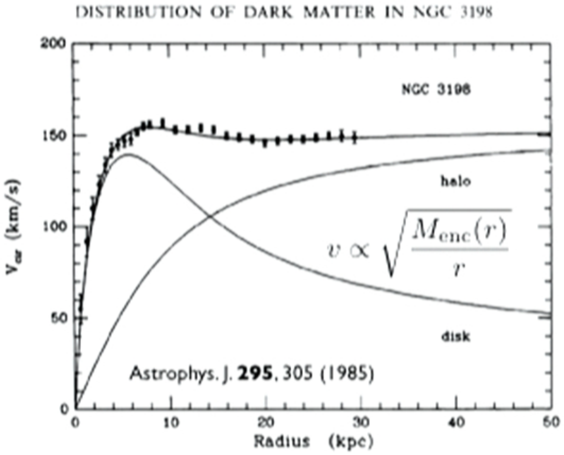
Perimeter Institute Particle Physics Seminar
Dec. 2, 2014

Based on:
Bridget Bertoni, Seyda Ipek, DM, & Ann Nelson, 1412.xxxx

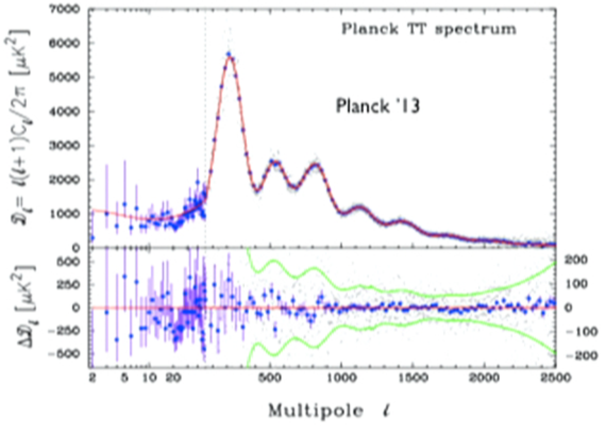
# Outline

- 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?

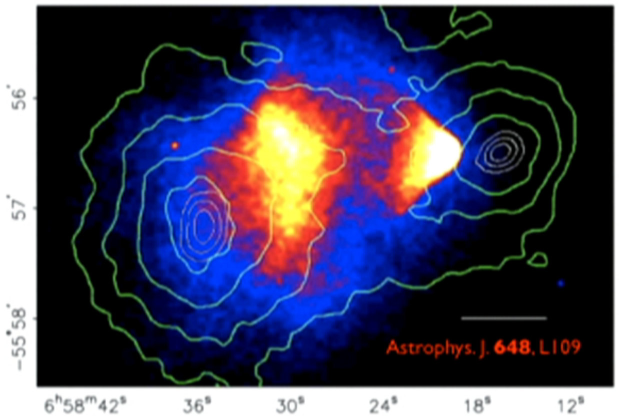
# Why Dark Matter?



Astrophys. J. **295**, 305 (1985)



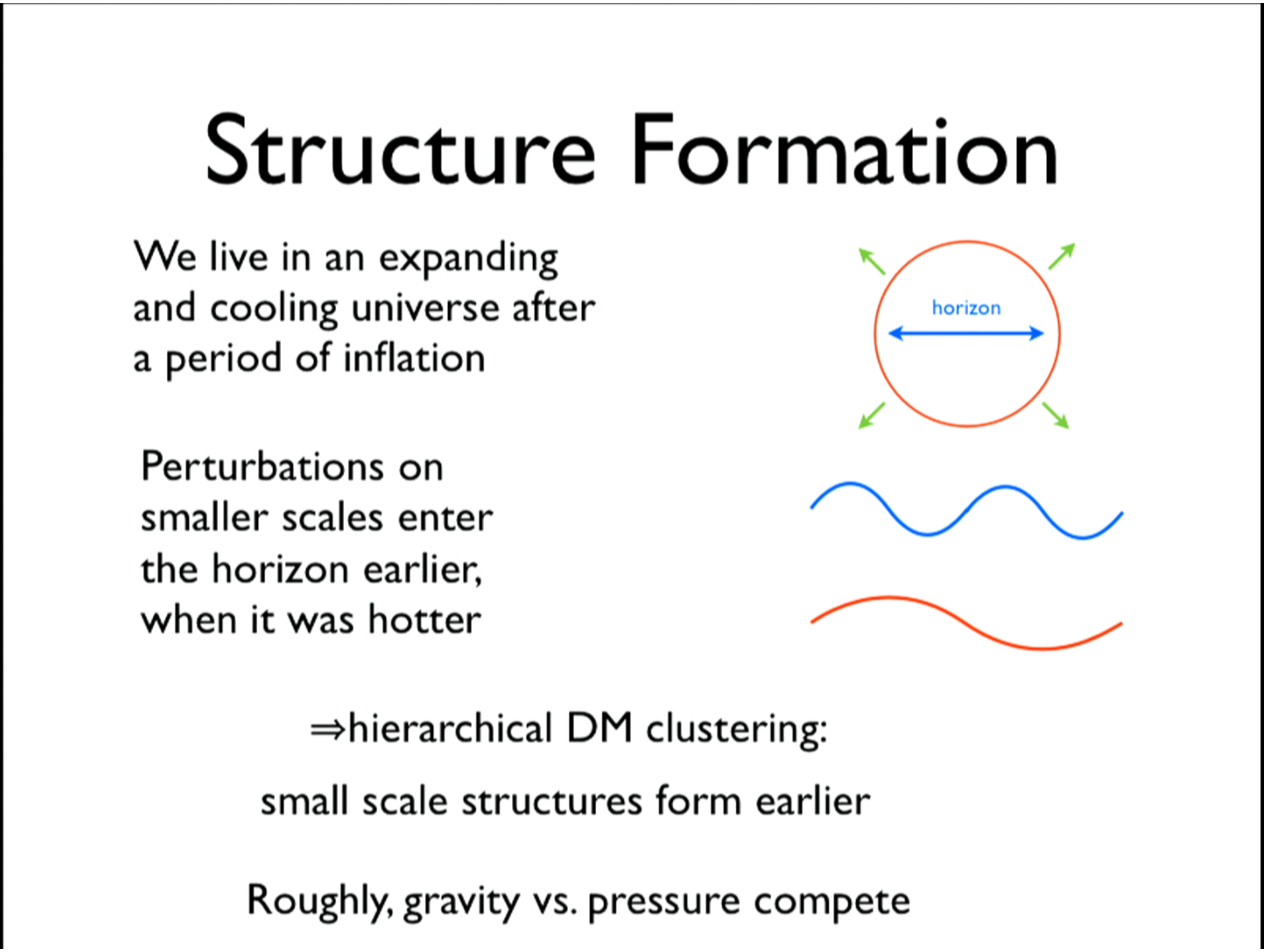
Planck '13



Astrophys. J. **648**, L109

$$\Omega_d \sim 0.2$$

$$\Omega_b \sim 0.04$$



# 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

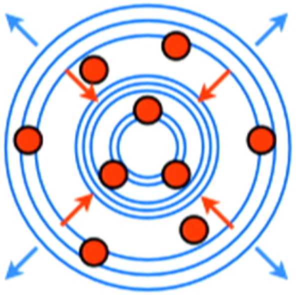
⇒hierarchical DM clustering:

small scale structures form earlier

Roughly, gravity vs. pressure compete

# Acoustic Oscillations

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



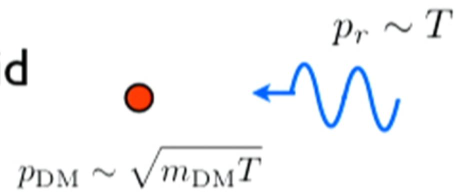
$$H_{\rm d}^{-1} = a_{\rm d}\eta_{\rm d}, \;\; \eta_{\rm d} = \int_0^{t_{\rm d}} \frac{dt}{a(t)}$$

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)



$$p_r \sim T$$

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

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

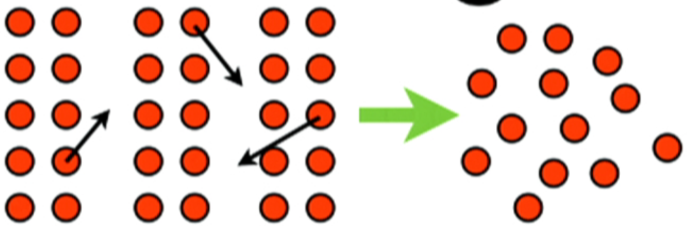
$$\Delta p_{\mathrm{tot}} \sim \sqrt{N} T \sim p_{\mathrm{DM}}$$
$$\Rightarrow N \sim \frac{m_{\mathrm{DM}}}{T}$$

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

Temperature at decoupling estimated:

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

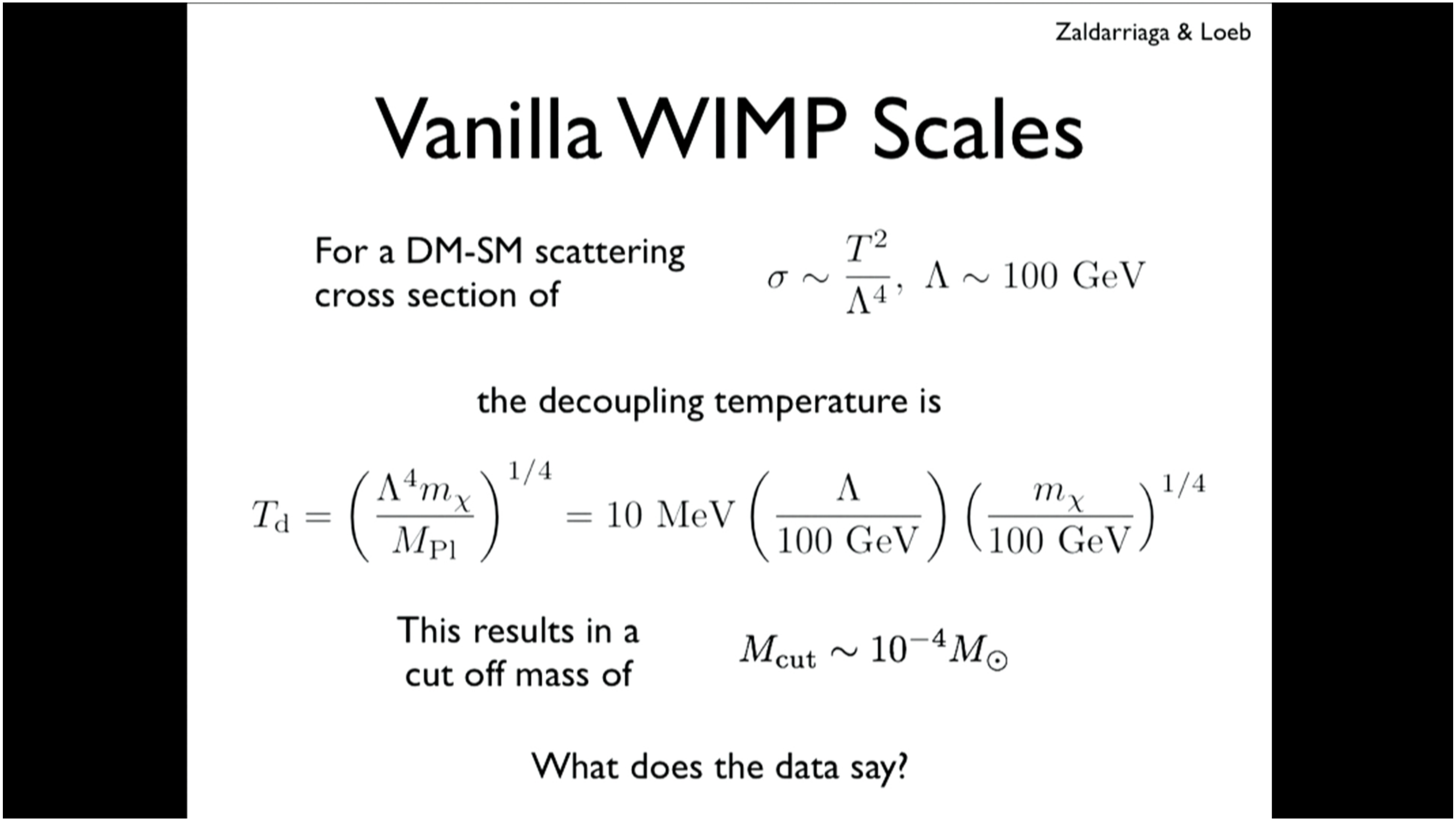
# DM Free Streaming



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

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

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



Zaldarriaga & Loeb

# Vanilla WIMP Scales

For a DM-SM scattering cross section of $\sigma \sim \frac{T^2}{\Lambda^4},\ \Lambda \sim 100\ \mathrm{GeV}$

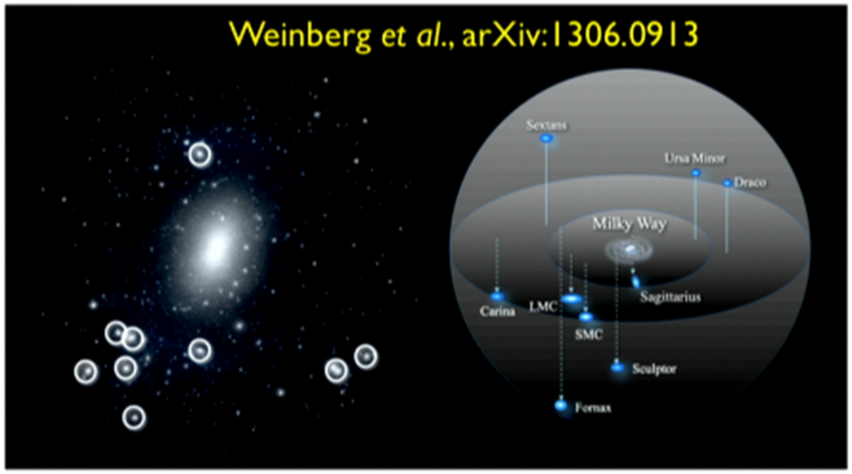
the decoupling temperature is

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

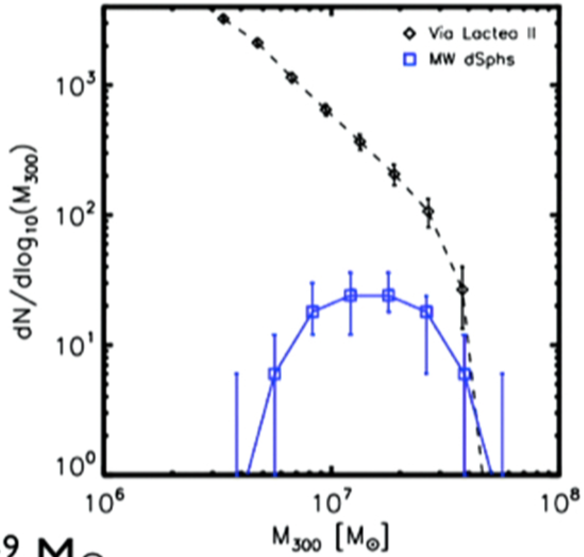
This results in a cut off mass of $M_{\rm cut} \sim 10^{-4} M_\odot$

What does the data say?

# Missing Satellites


Weinberg *et al.*, arXiv:1306.0913

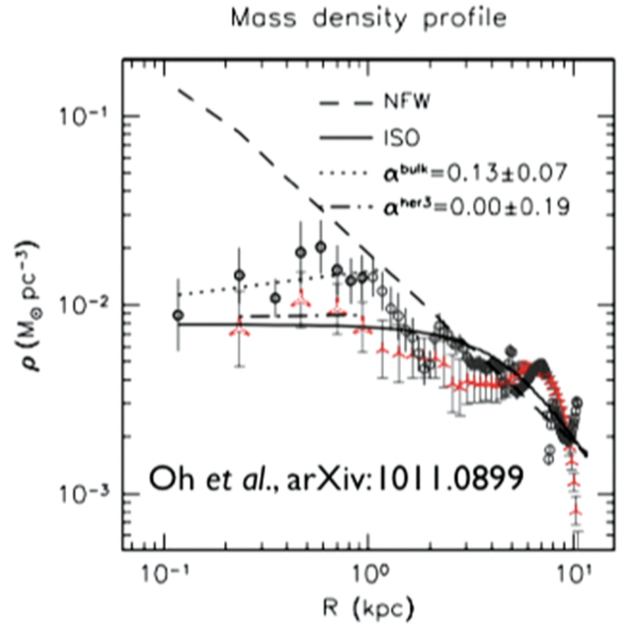
Bullock, arXiv:1009.4505



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

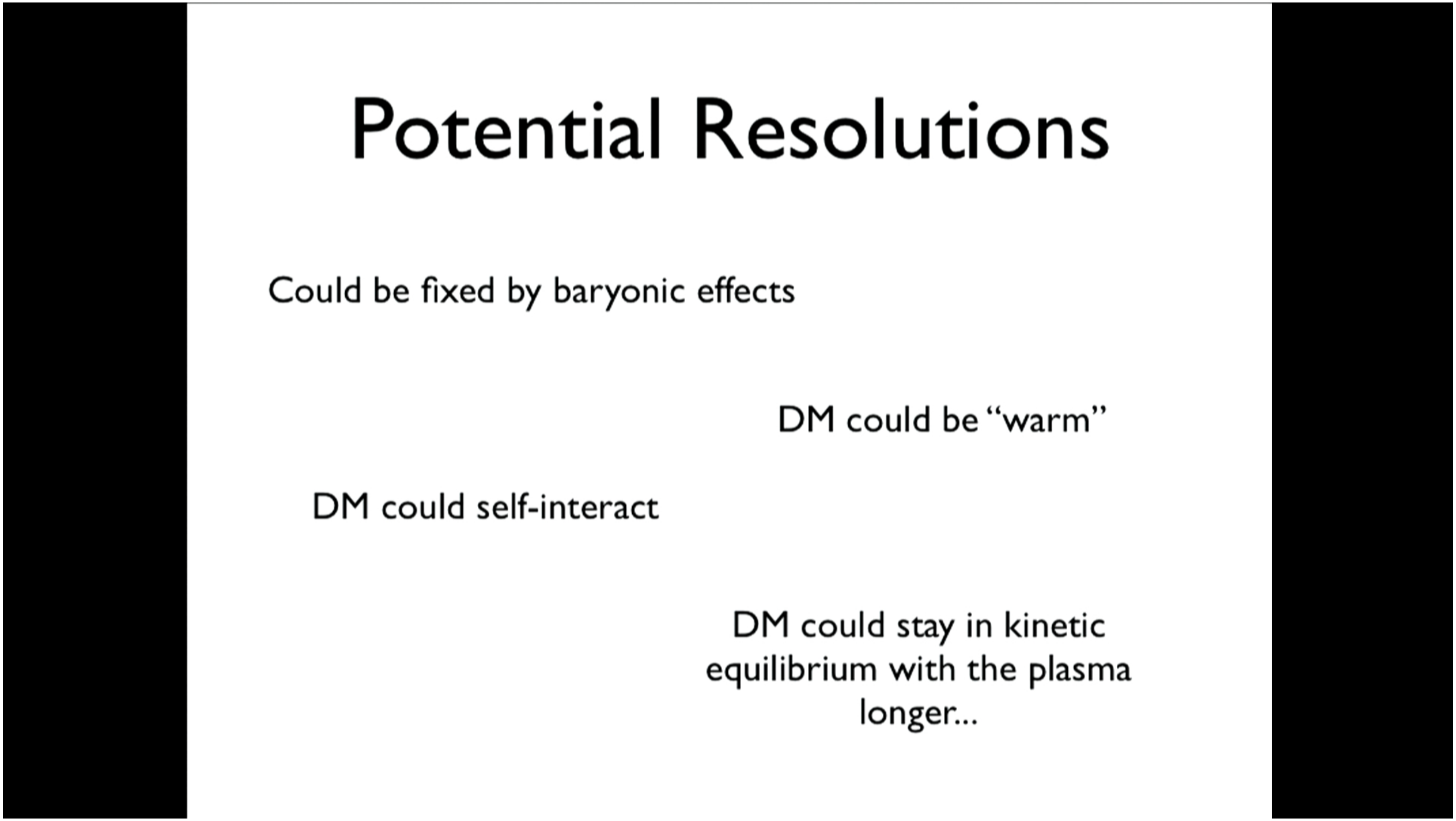


Oh *et al.*, arXiv:1011.0899

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”

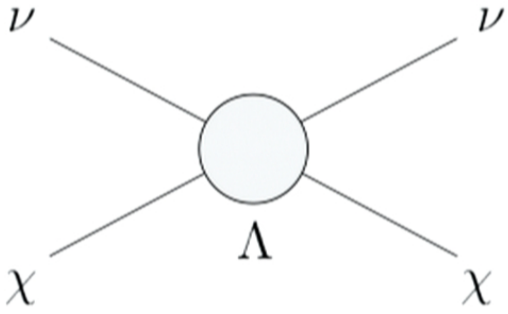
DM could self-interact

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

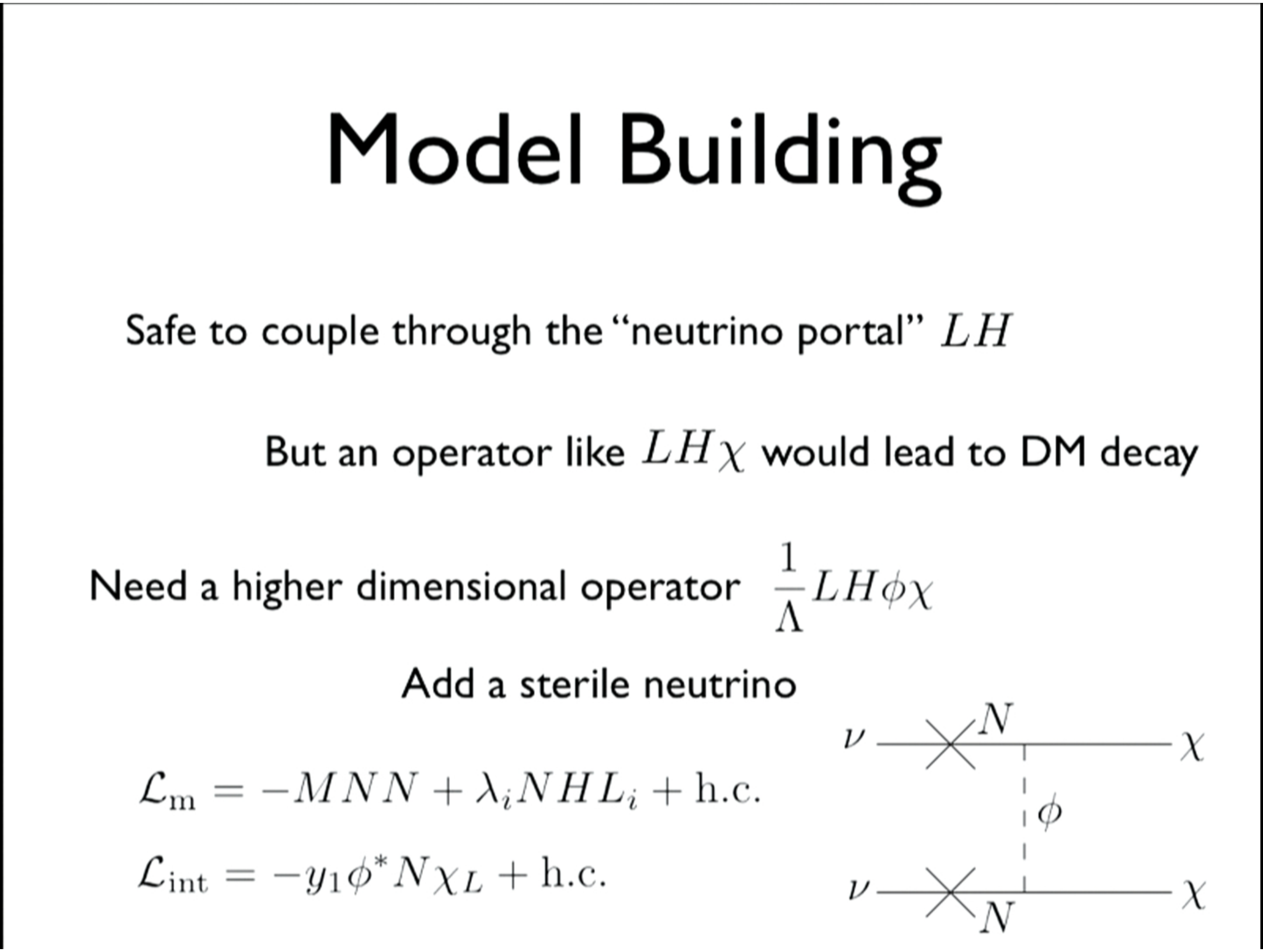
Want $T_{\rm d} \sim {\rm keV}$

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

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

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

What would a model of this look like?



# Model Building

Safe to couple through the "neutrino portal" $LH$

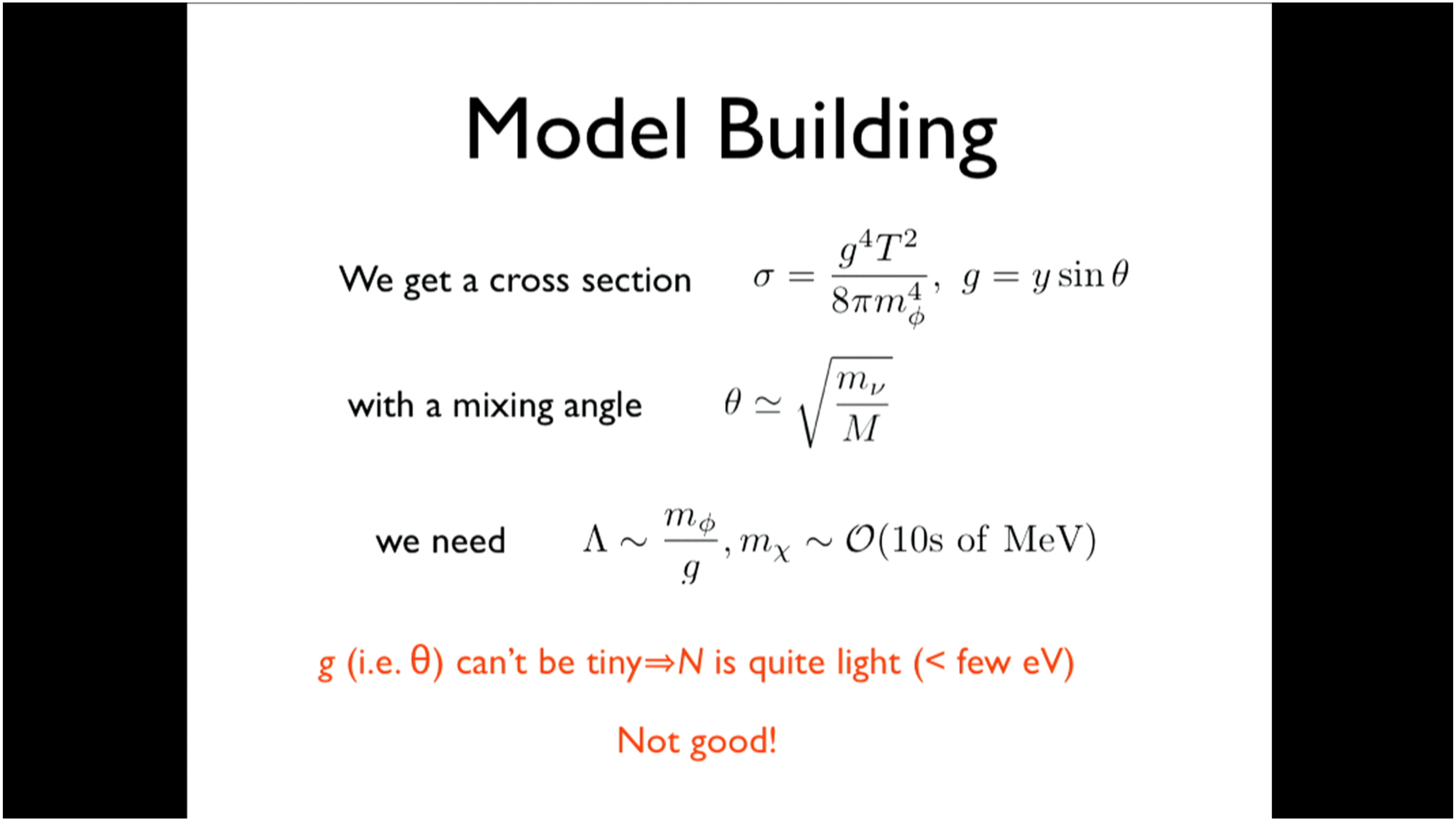
But an operator like $LH\chi$ would lead to DM decay

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

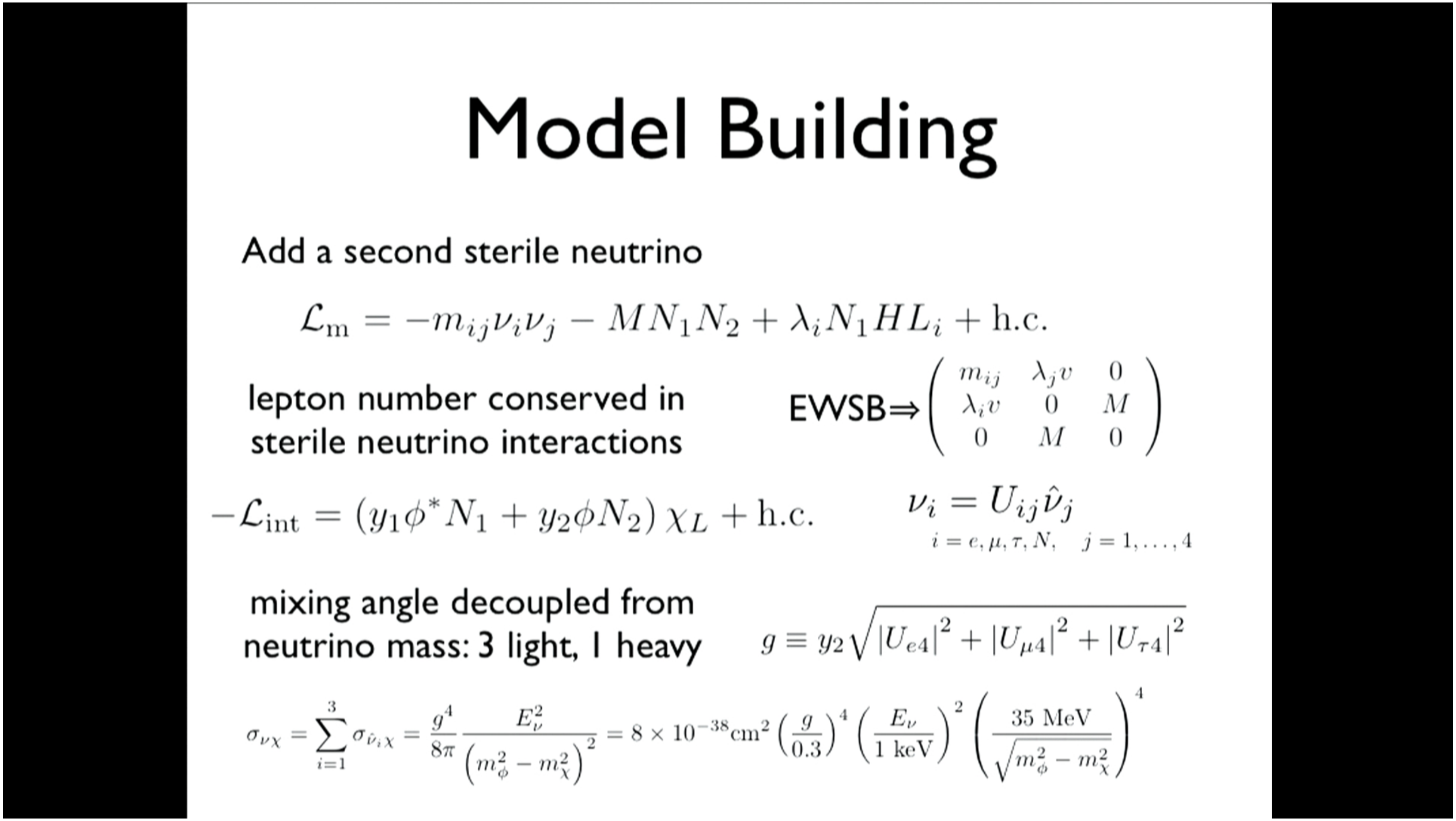
We get a cross section $\sigma = \frac{g^4 T^2}{8\pi m_\phi^4}, \ g = y \sin\theta$

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

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

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

Not good!



# Model Building

Add a second sterile neutrino

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

lepton number conserved in sterile neutrino interactions

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

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

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

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

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

$$g \equiv y_2\sqrt{|U_{e4}|^2 + |U_{\mu4}|^2 + |U_{\tau4}|^2}$$

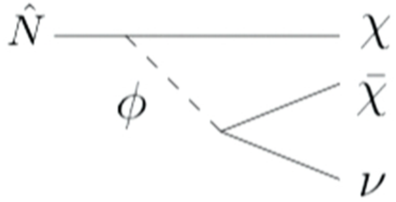
$$\sigma_{\nu\chi} = \sum_{i=1}^{3}\sigma_{\hat{\nu}_i\chi} = \frac{g^4}{8\pi}\frac{E_\nu^2}{\left(m_\phi^2 - m_\chi^2\right)^2} = 8\times10^{-38}\text{cm}^2\left(\frac{g}{0.3}\right)^4\left(\frac{E_\nu}{1\text{ keV}}\right)^2\left(\frac{35\text{ MeV}}{\sqrt{m_\phi^2 - m_\chi^2}}\right)^4$$

# 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

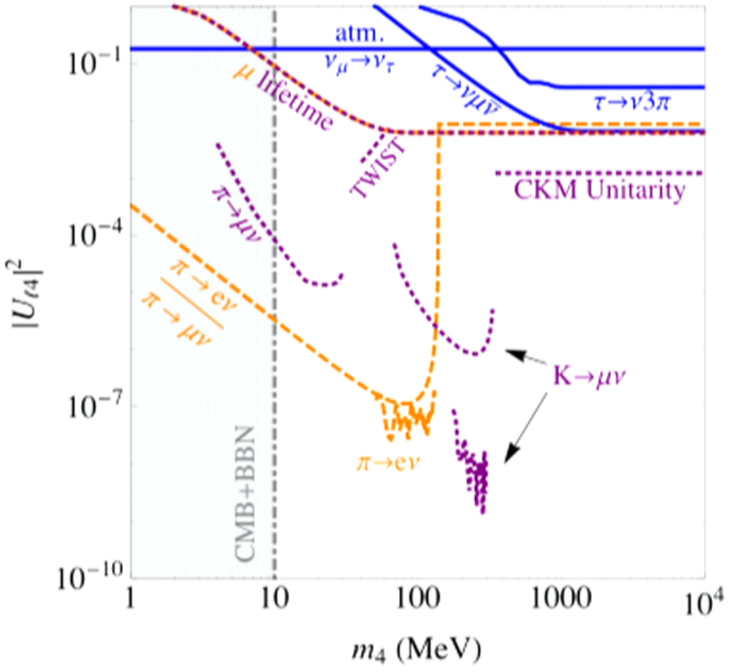


$$\Gamma_{\hat{N}\to\nu\chi\bar{\chi}} = \frac{\left(y_1^2 + y_2^2 c_\theta^2\right) m_4}{32\pi} \simeq 3 \text{ MeV} \left(\frac{m_4}{300 \text{ MeV}}\right)$$

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?

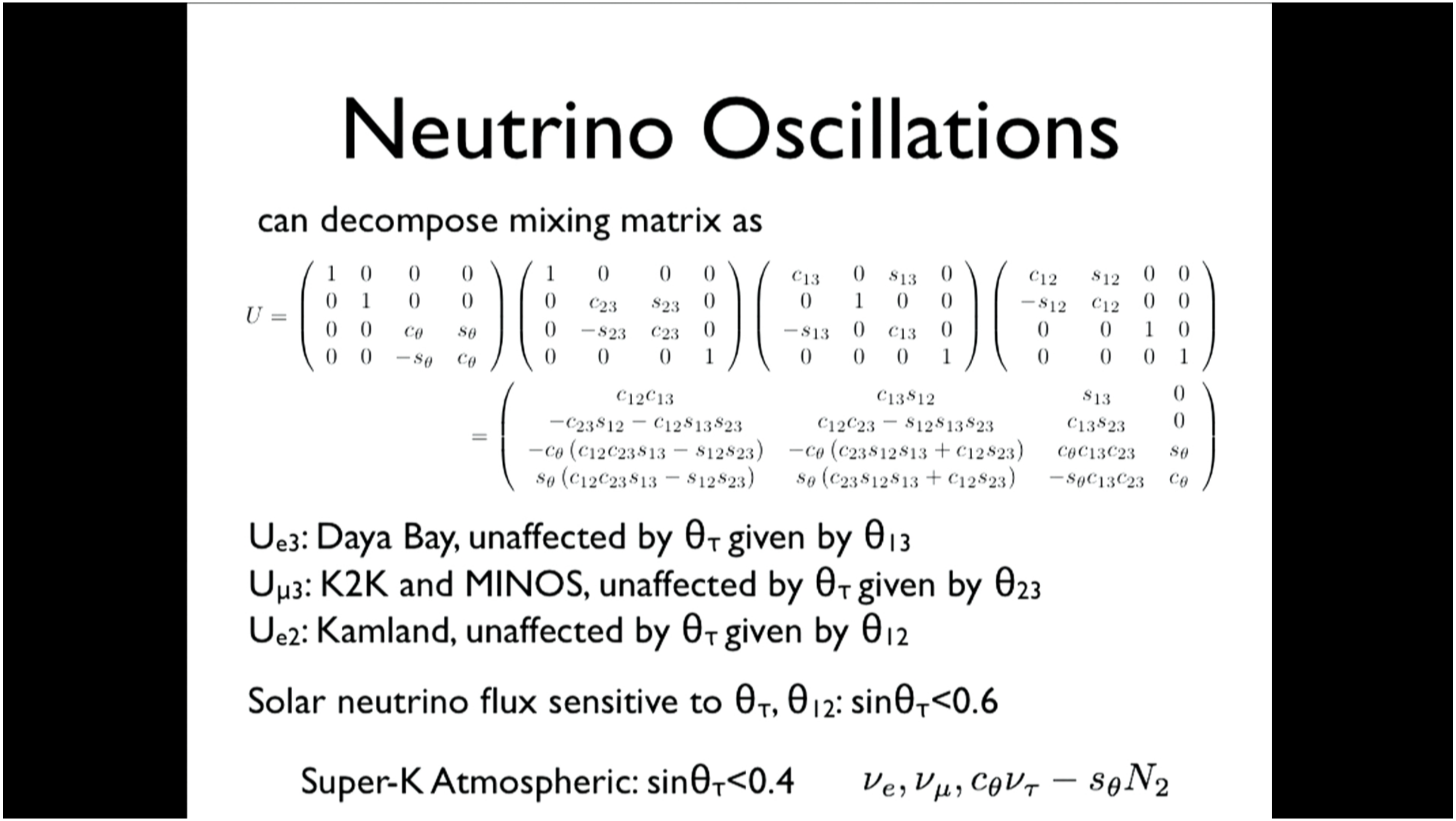


**Require:**

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

⇒couple to the

τ neutrino



# Neutrino Oscillations

can decompose mixing matrix as

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

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

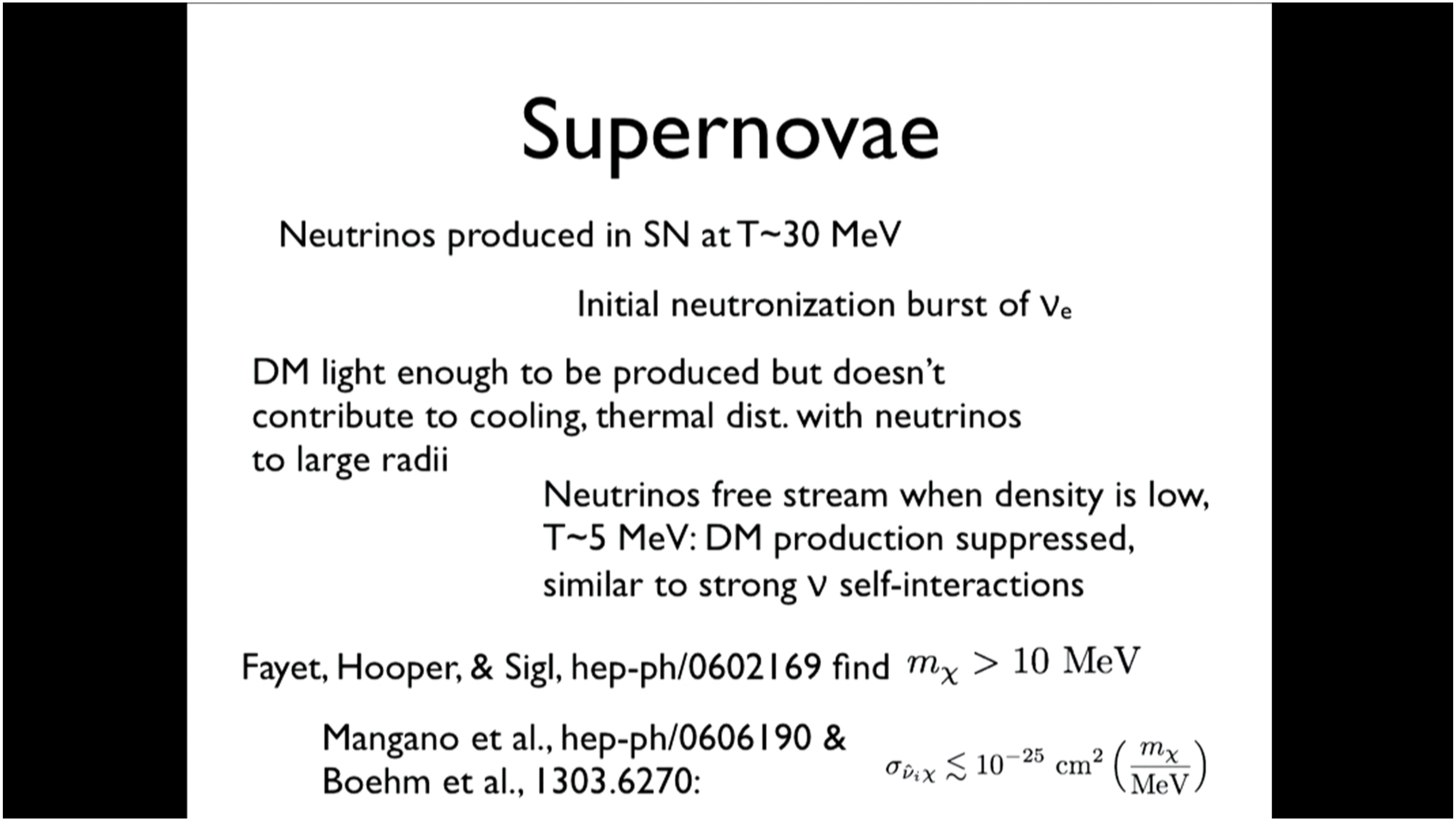
$U_{e3}$: Daya Bay, unaffected by $\theta_\tau$ given by $\theta_{13}$

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

$U_{e2}$: Kamland, unaffected by $\theta_\tau$ given by $\theta_{12}$

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

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



# Supernovae

Neutrinos produced in SN at T~30 MeV

Initial neutronization burst of $\nu_e$

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 $\nu$ self-interactions

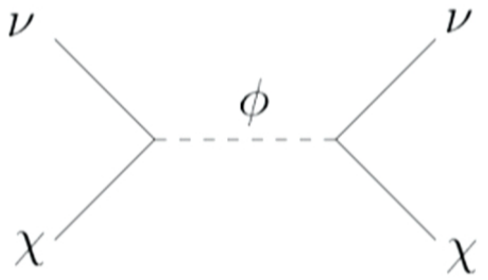
Fayet, Hooper, & Sigl, hep-ph/0602169 find $m_\chi > 10\ \mathrm{MeV}$

Mangano et al., hep-ph/0606190 &
Boehm et al., 1303.6270:

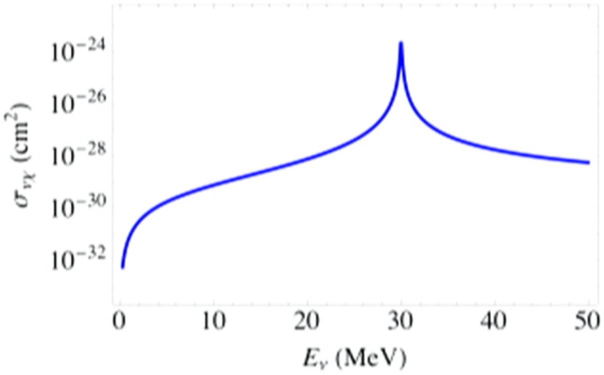
$$\sigma_{\hat{\nu}_i\chi} \lesssim 10^{-25}\ \mathrm{cm}^2 \left(\frac{m_\chi}{\mathrm{MeV}}\right)$$

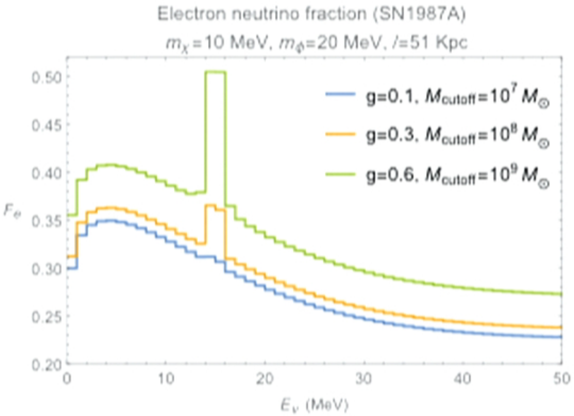
# Neutrinos from SN

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



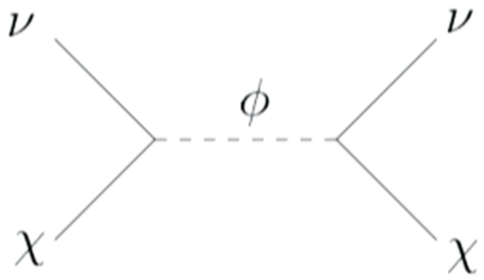


$\mathrm{Flux}_i \propto e^{-\Gamma_i d}$ $\quad \Gamma = \sigma_{\nu\chi} \times \dfrac{1}{d}\displaystyle\int dx\, n_\chi$

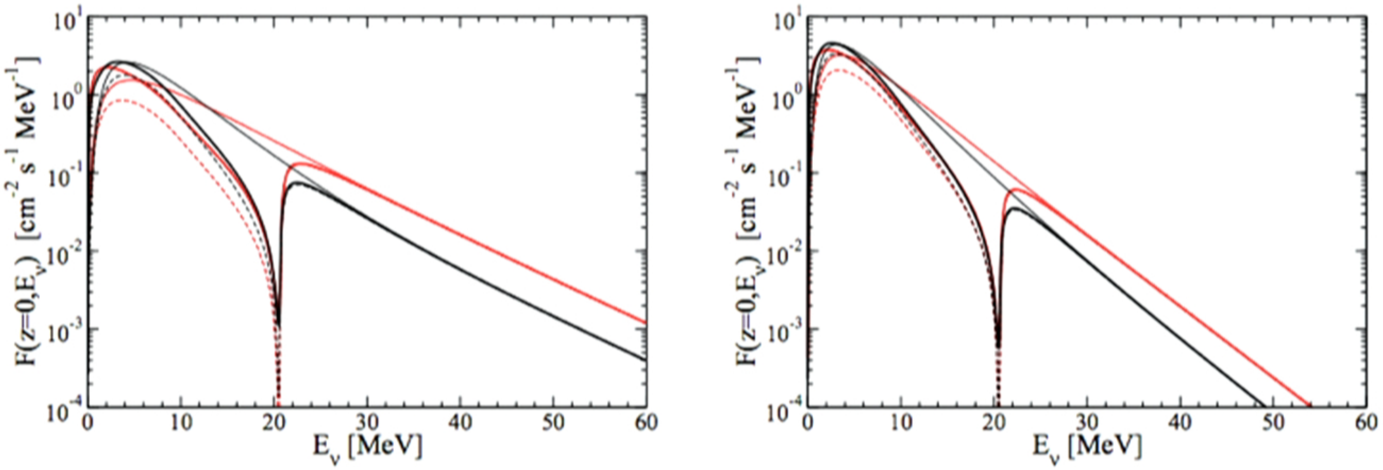
$$\frac{1}{\Gamma_1} \simeq \frac{6}{\Gamma}, \quad \frac{1}{\Gamma_2} \simeq \frac{3}{\Gamma}, \quad \frac{1}{\Gamma_3} \simeq \frac{2}{\Gamma}$$

# DSNB

Same process as for nearby SN



Farzan & Palomares-Ruiz 1401.7019



Potentially visible at Hyper-K

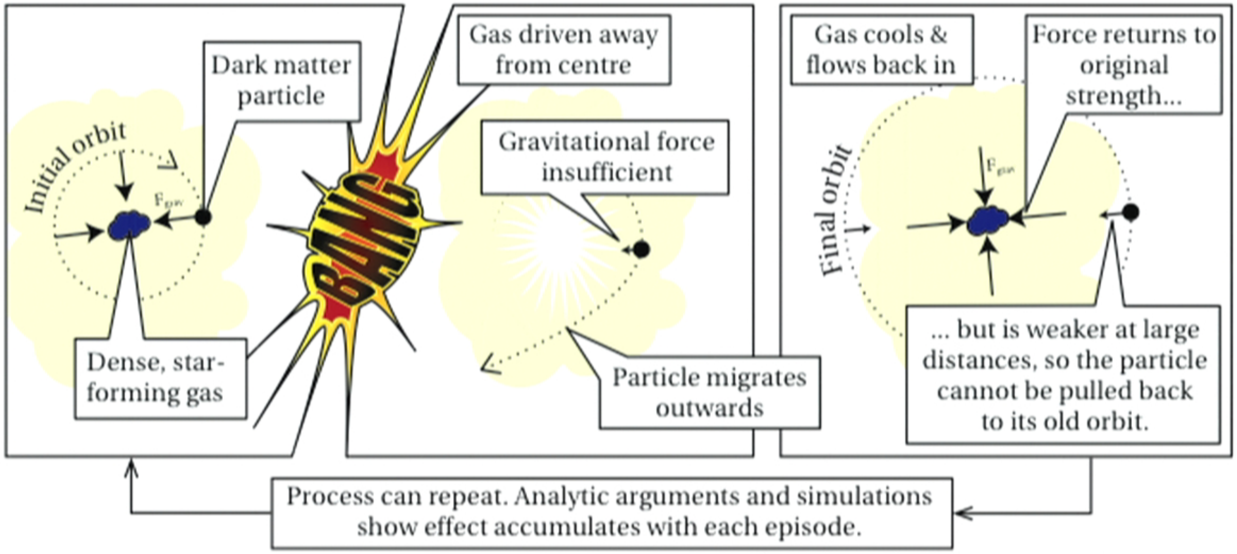
# Neutrinos from SN:
# Core vs. Cusp?

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

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

transferred from SN to DM

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



Dark matter particle

Dense, star-forming gas

Gas driven away from centre

Gravitational force insufficient

Particle migrates outwards

Gas cools & flows back in

Force returns to original strength...

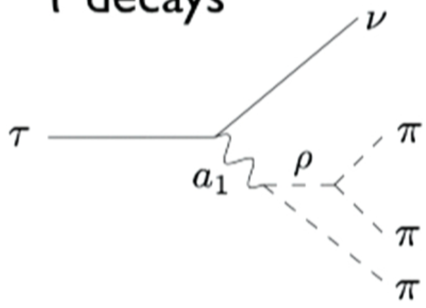
... but is weaker at large distances, so the particle cannot be pulled back to its old orbit.

Process can repeat. Analytic arguments and simulations show effect accumulates with each episode.

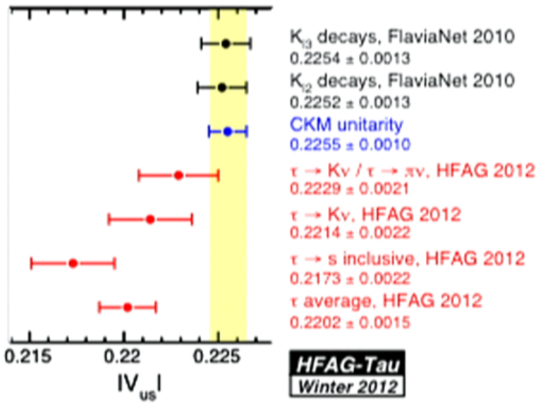
Pontzen & Governato, 1402.1764

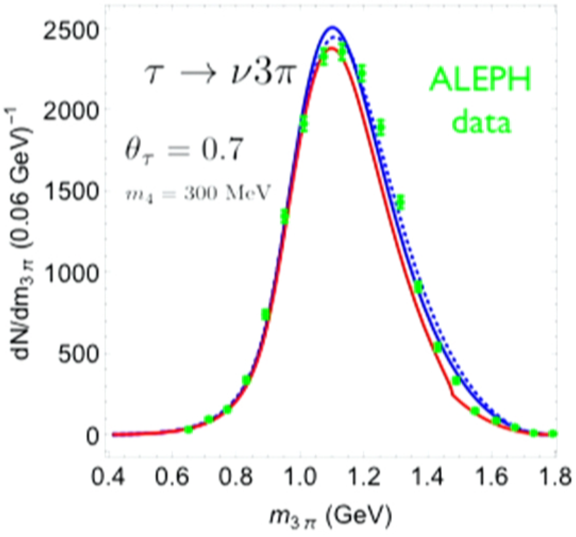
# Future tests

τ decays



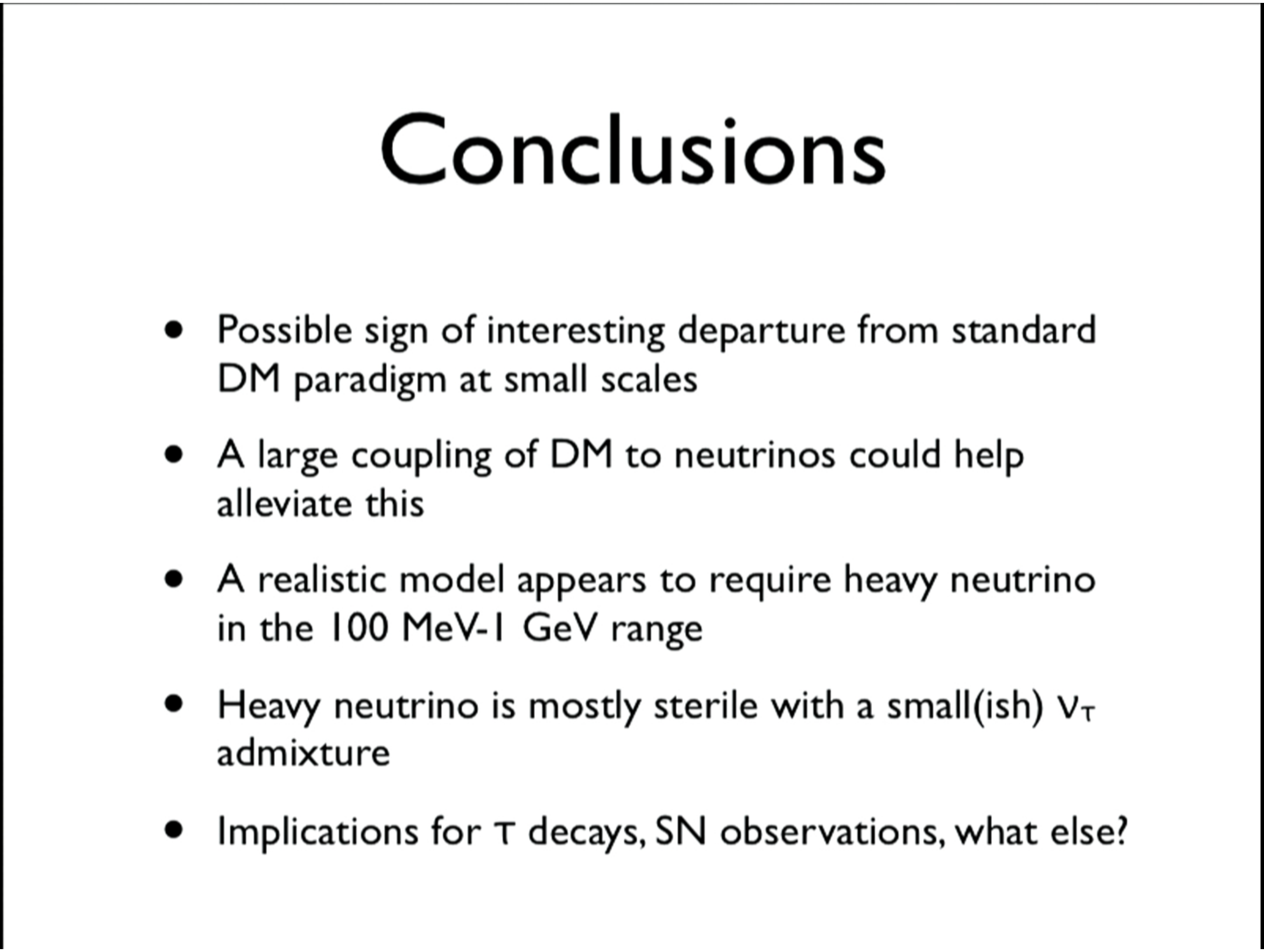
τ→K decays slightly low...





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) $\nu_\tau$ admixture
- Implications for $\tau$ decays, SN observations, what else?