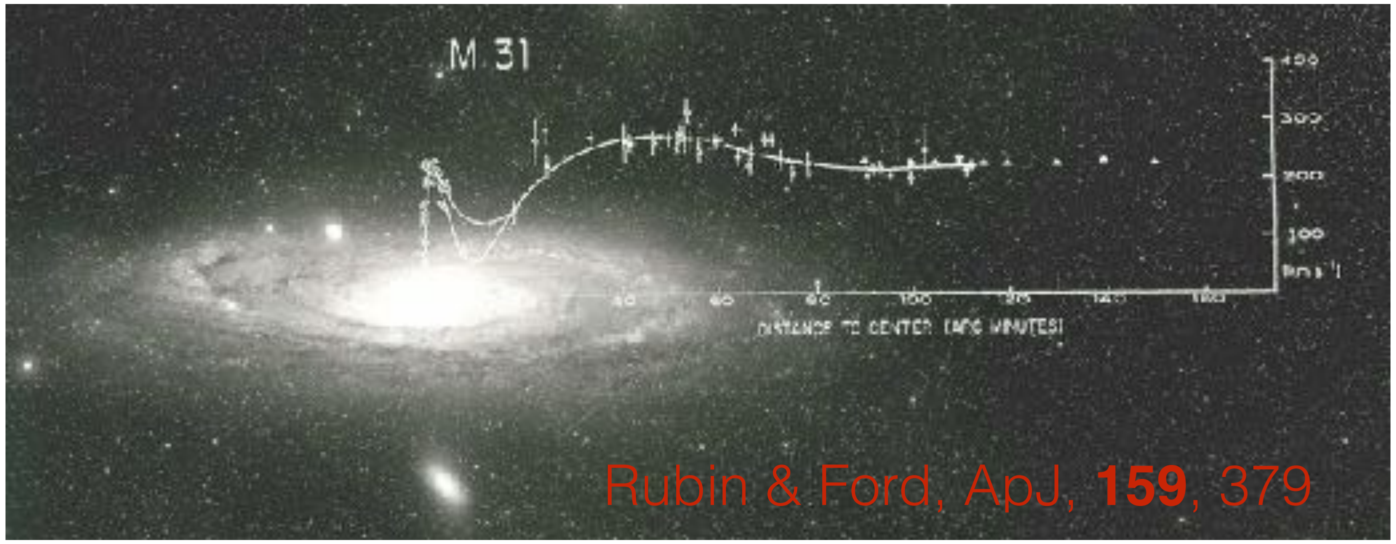
Dark Matter-Neutrino Interactions

David McKeen
University of Pittsburgh

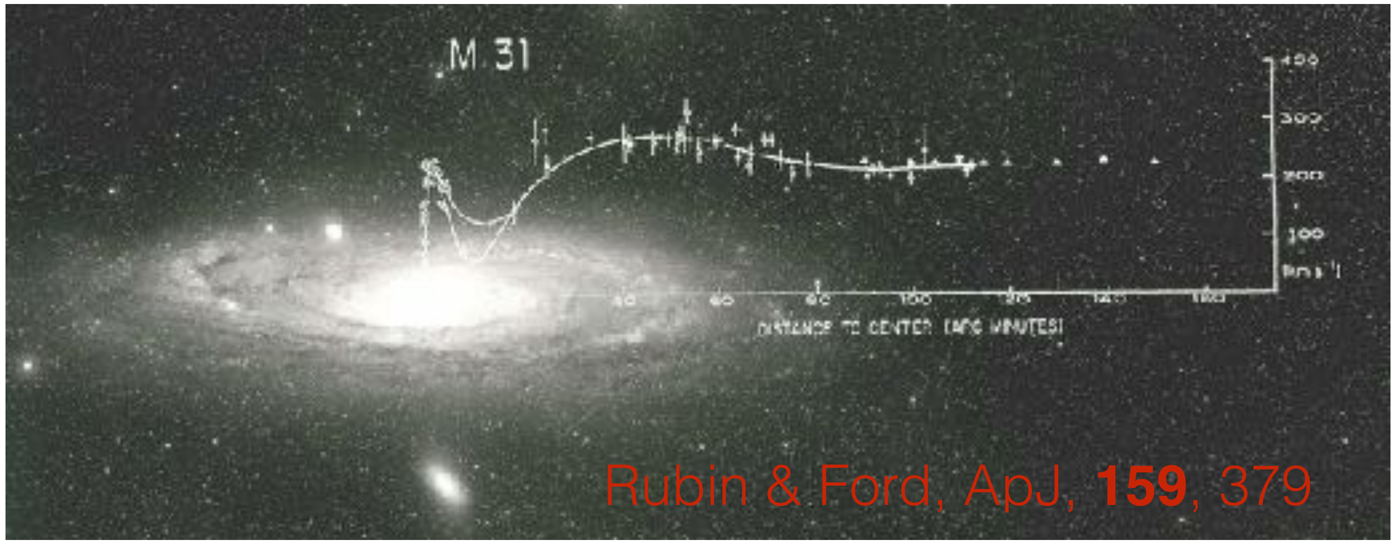
CERN-EPFL-Korea TH Institute “New Physics at the Intensity Frontier”, March 3, 2017

Based on work with Bridget Bertoni, Seyda Ipek, and Ann Nelson

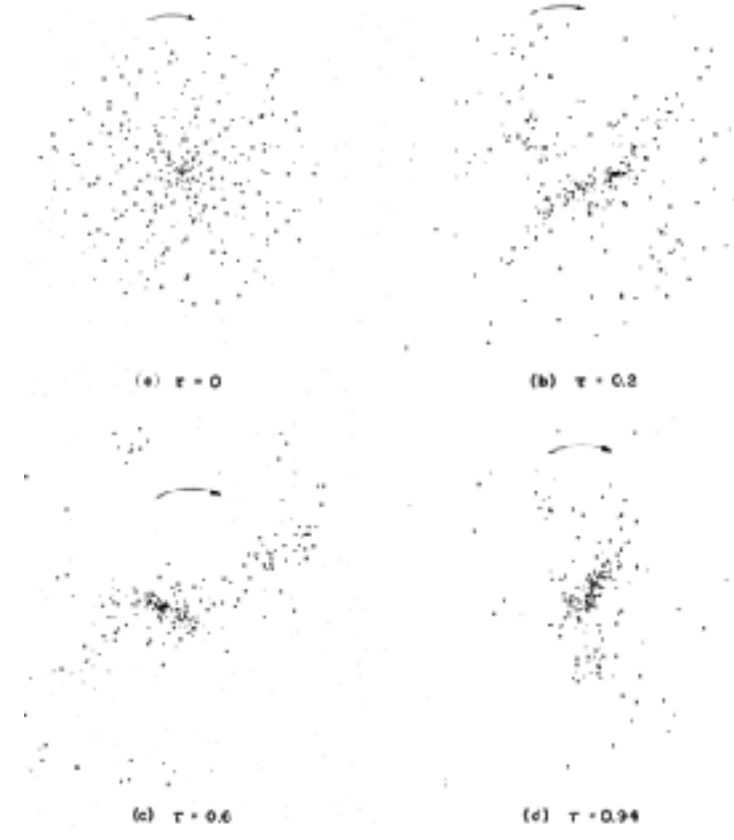
Why Dark Matter?

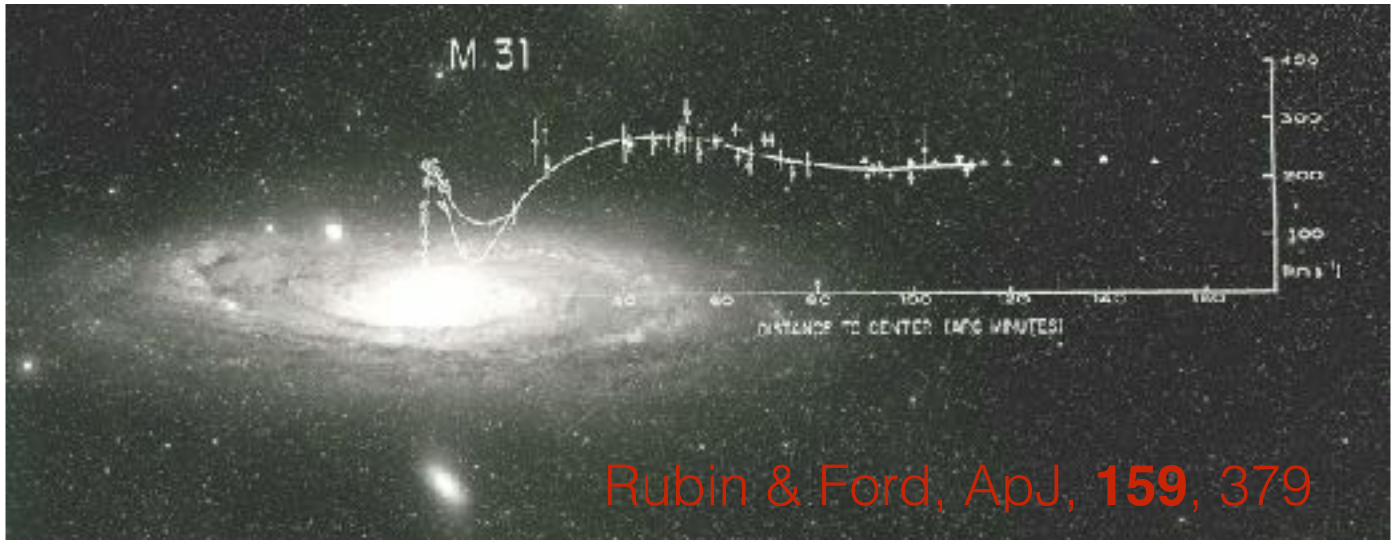

M 31
DISTANCE TO CENTER (ARC MINUTES)
Rubin & Ford, ApJ, **159**, 379

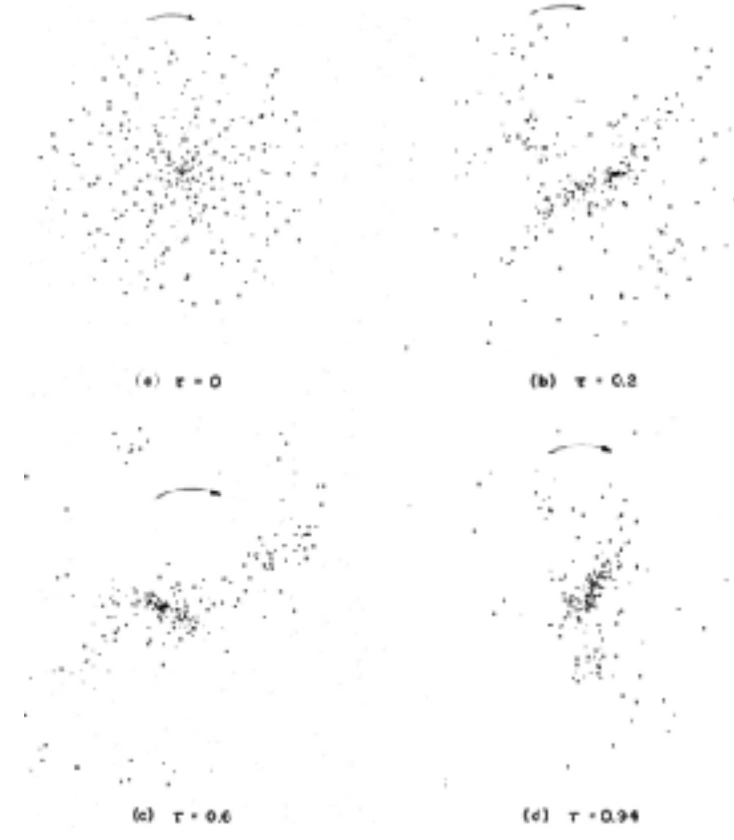
Ostriker & Peebles, ApJ, **186**, 467 ('73)



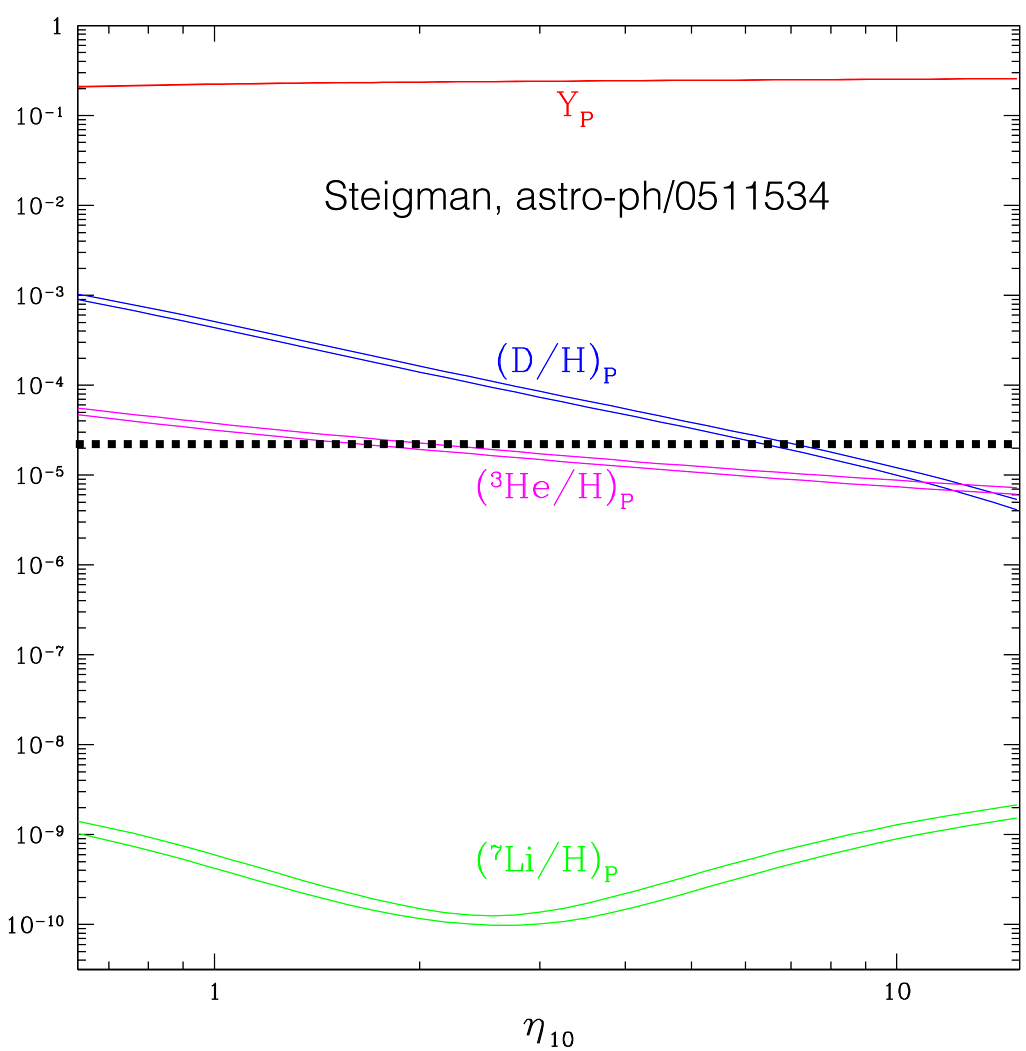
Rubin & Ford, ApJ, **159**, 379



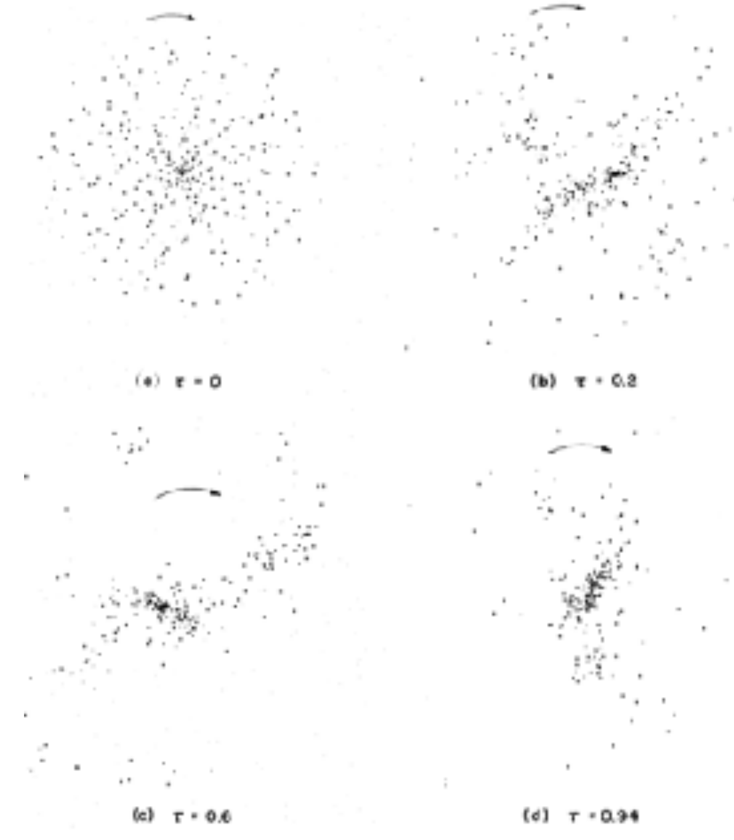


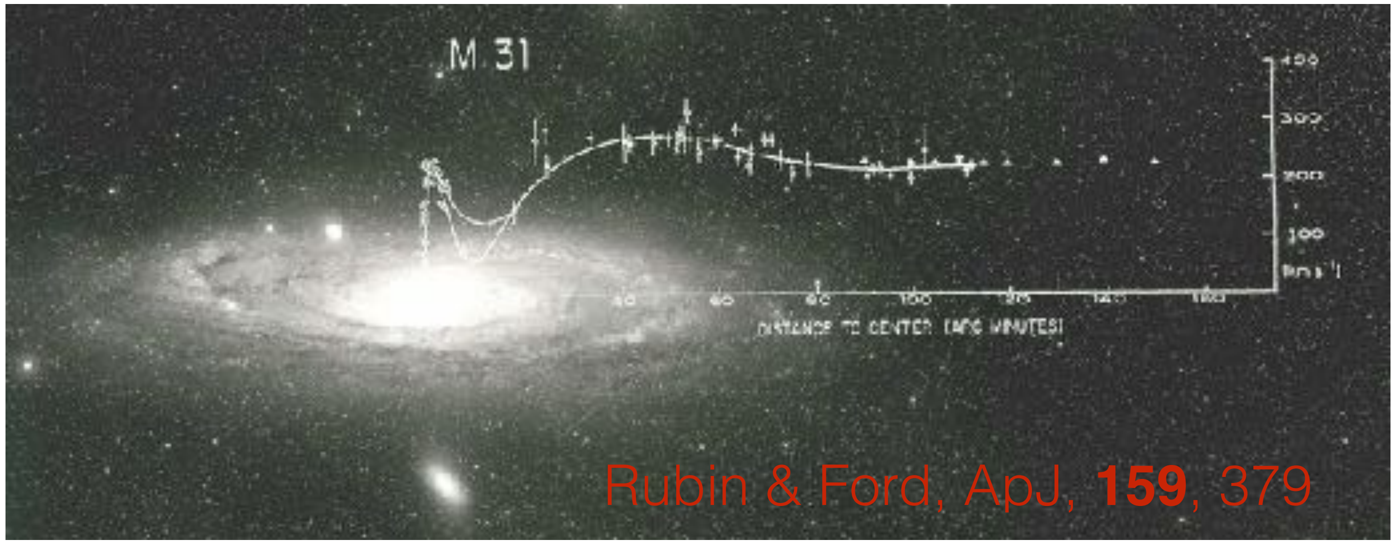


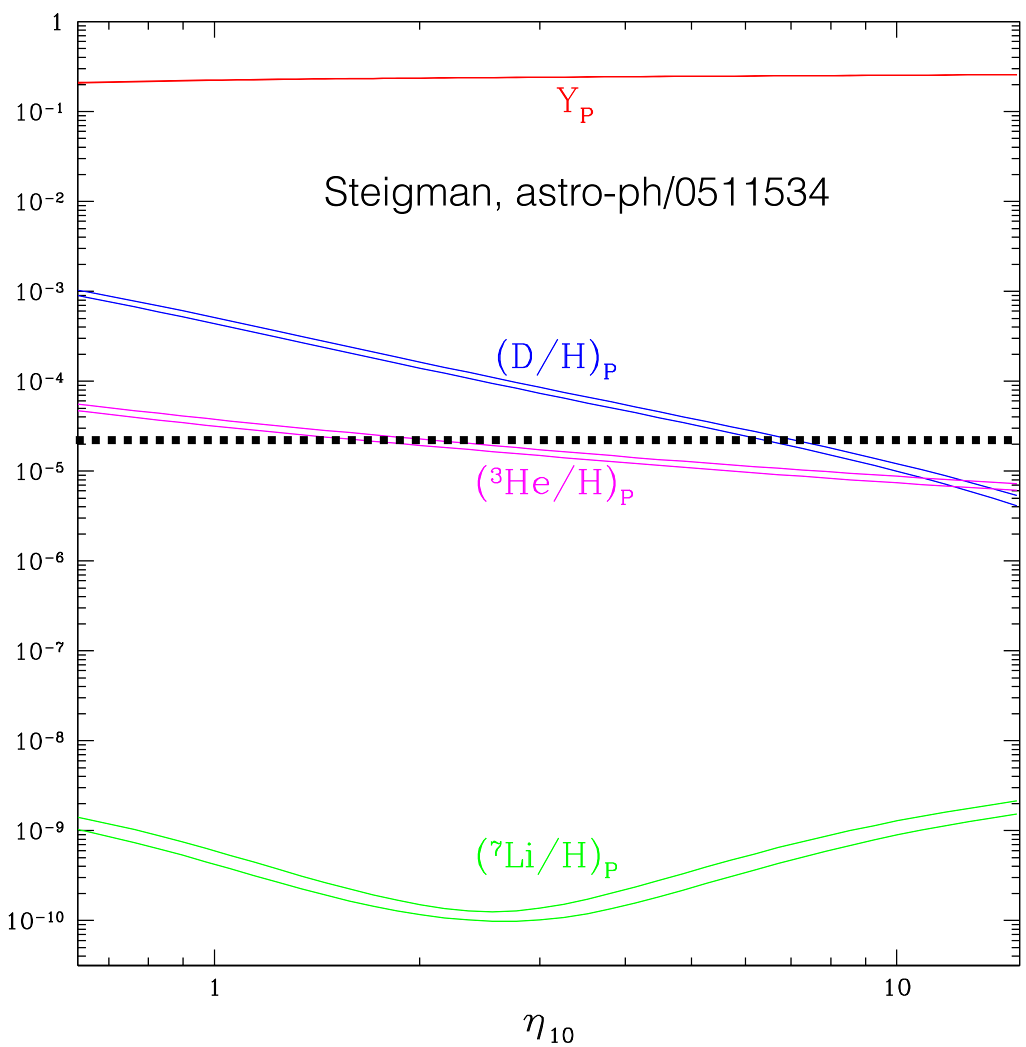
Ostriker & Peebles, ApJ, **186**, 467 ('73)

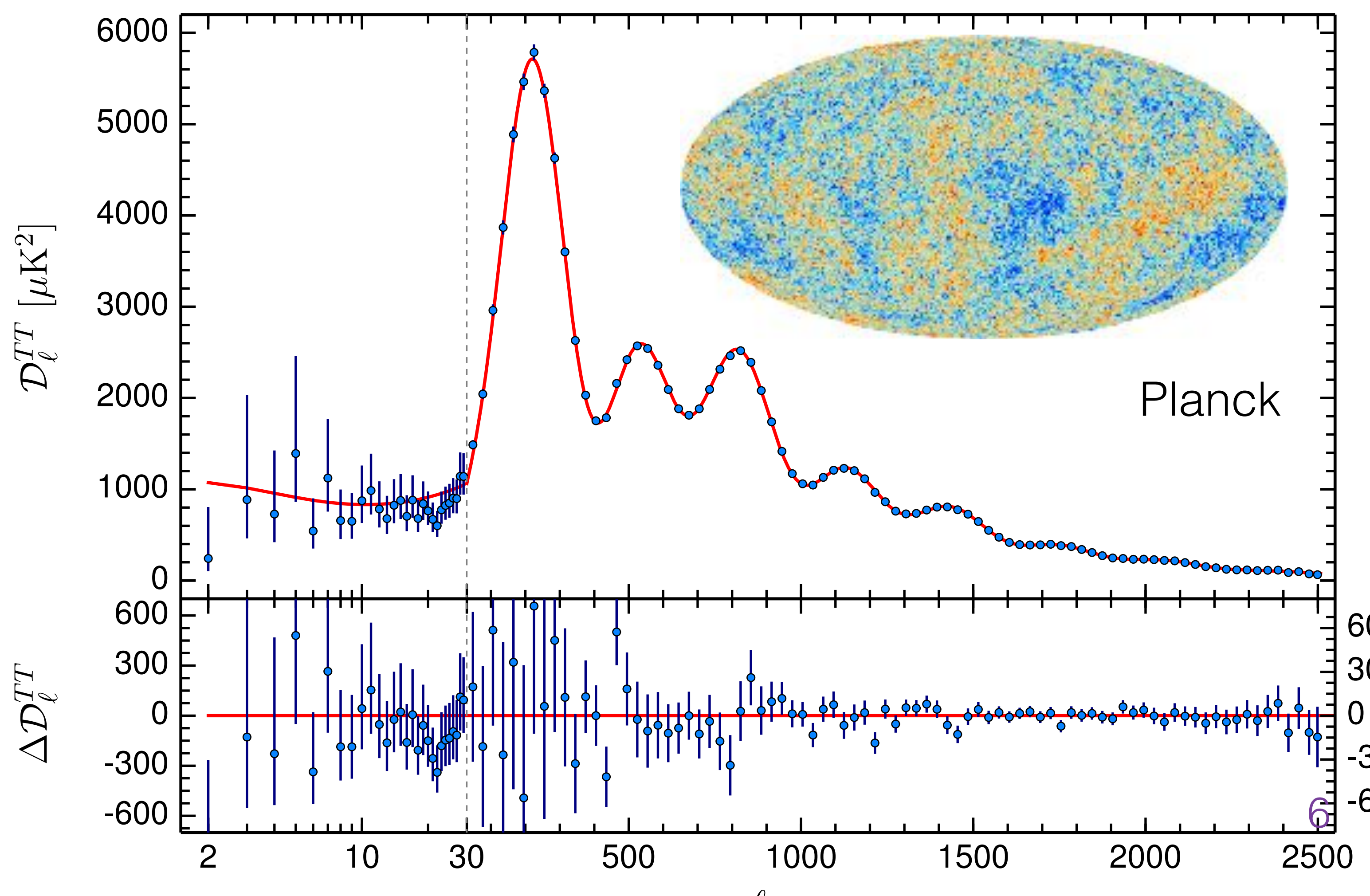


Ostriker & Peebles, ApJ, **186**, 467 ('73)

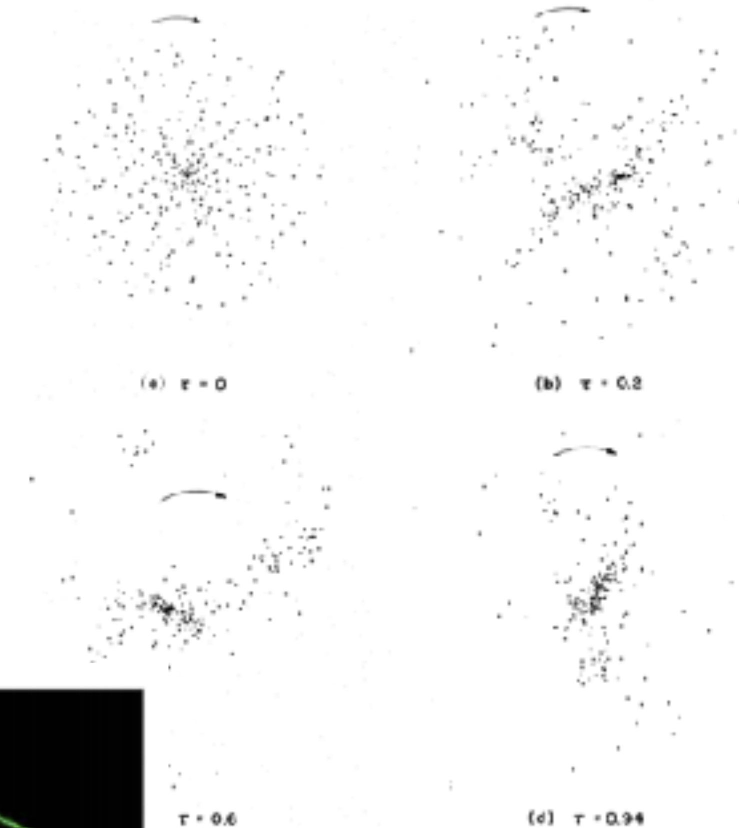


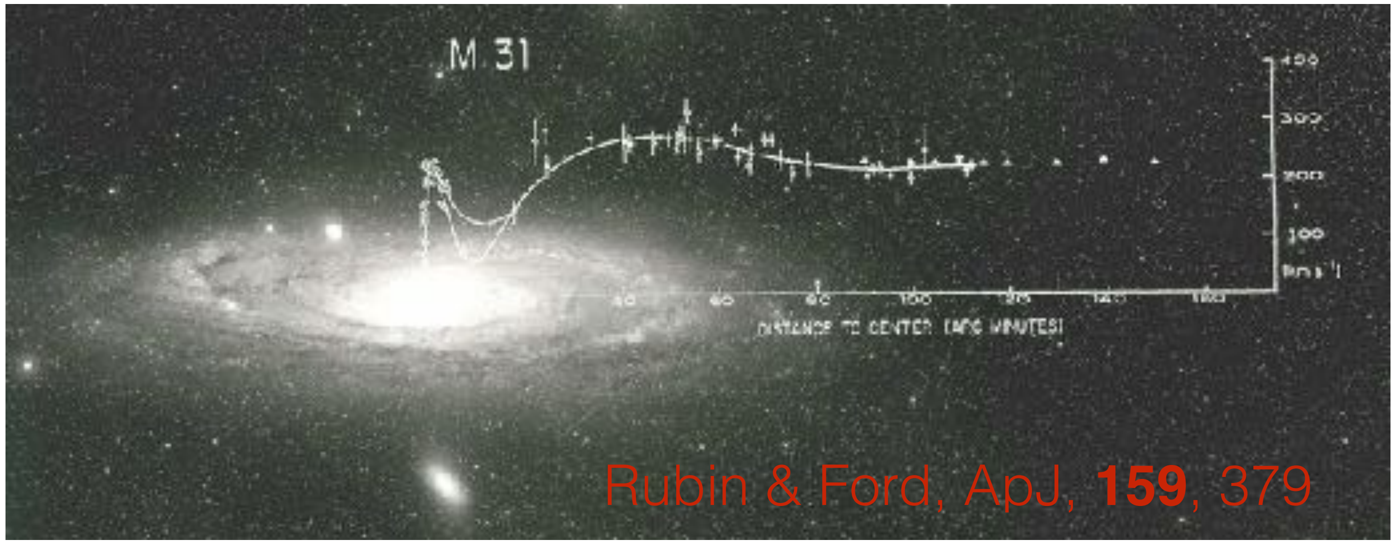


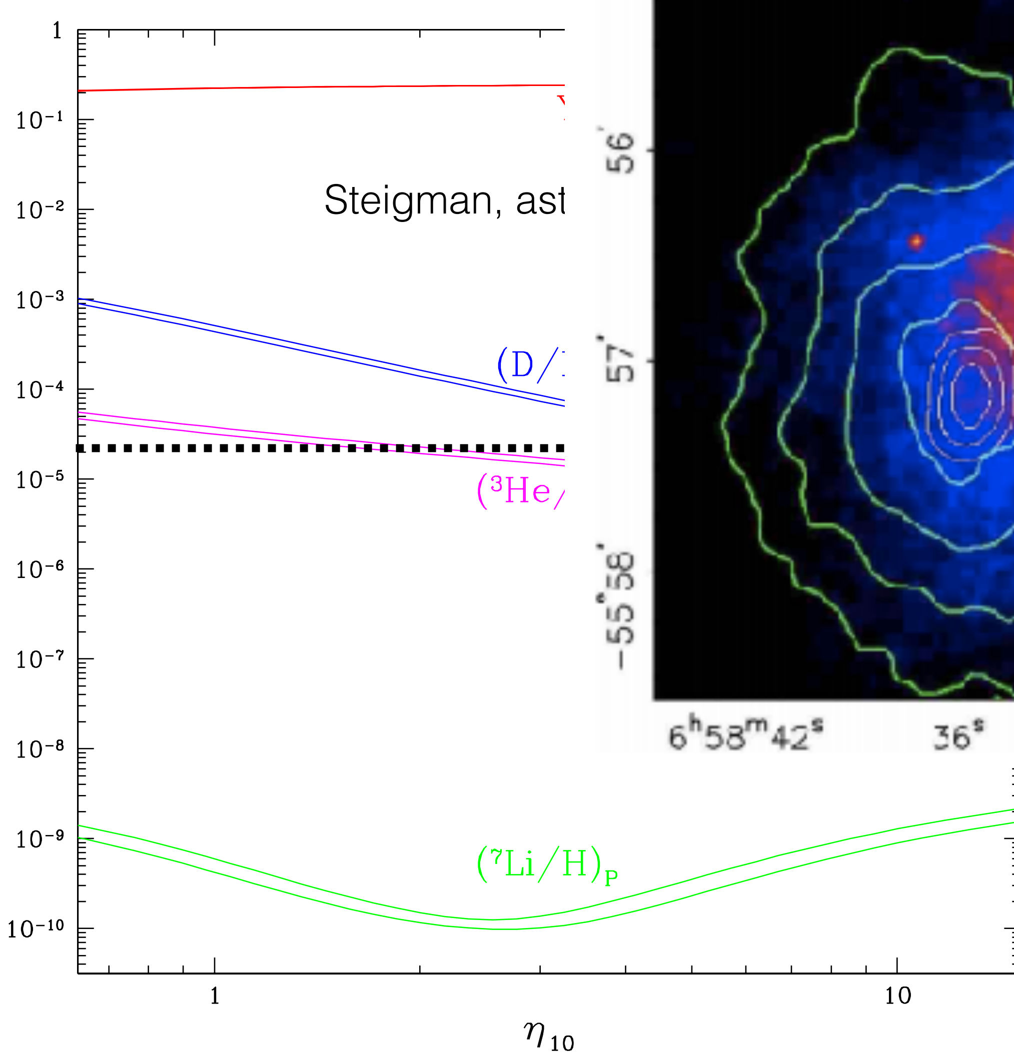


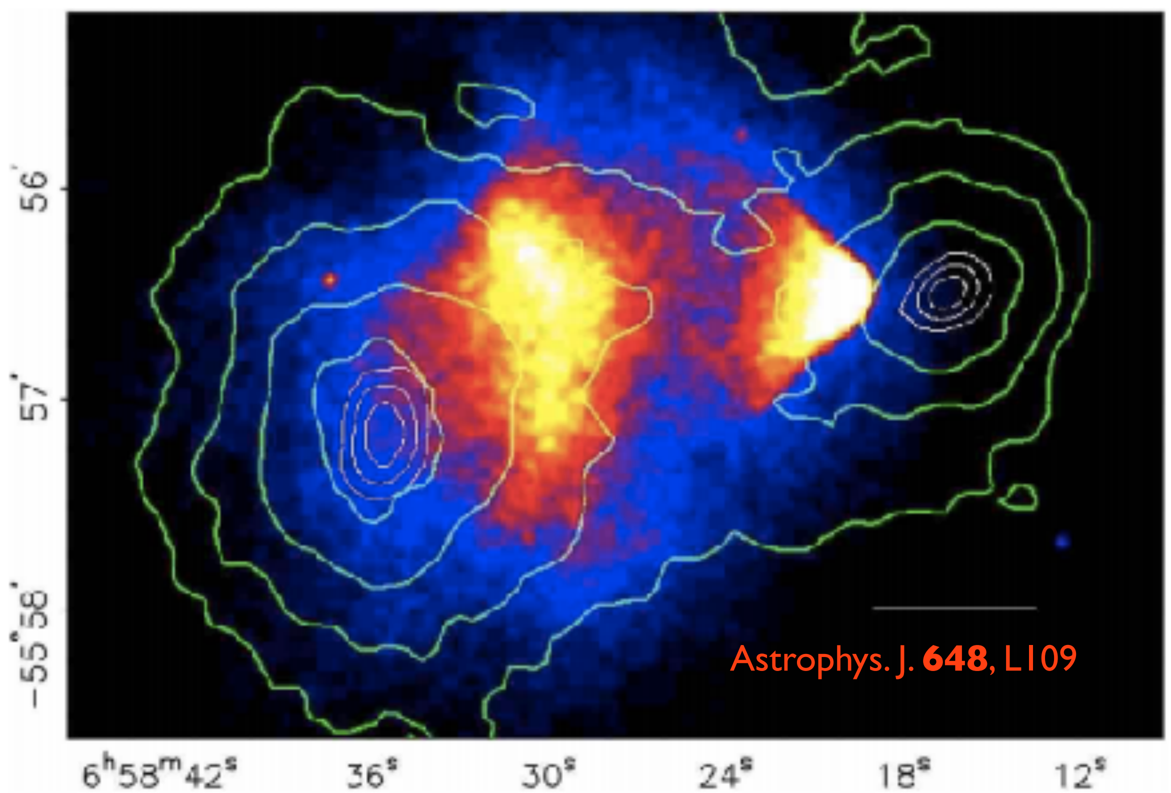


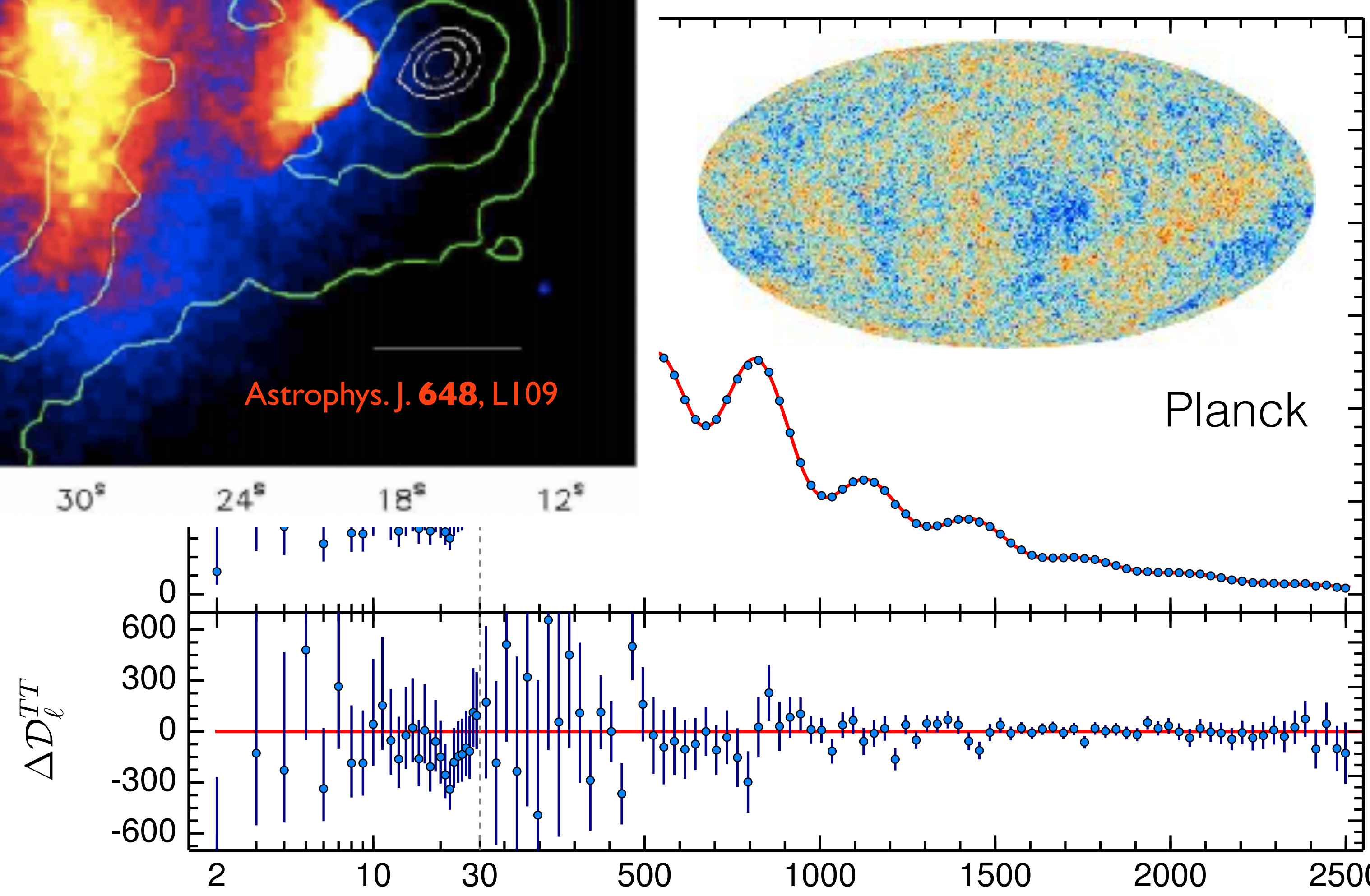
Ostriker & Peebles, ApJ, **186**, 467 ('73)



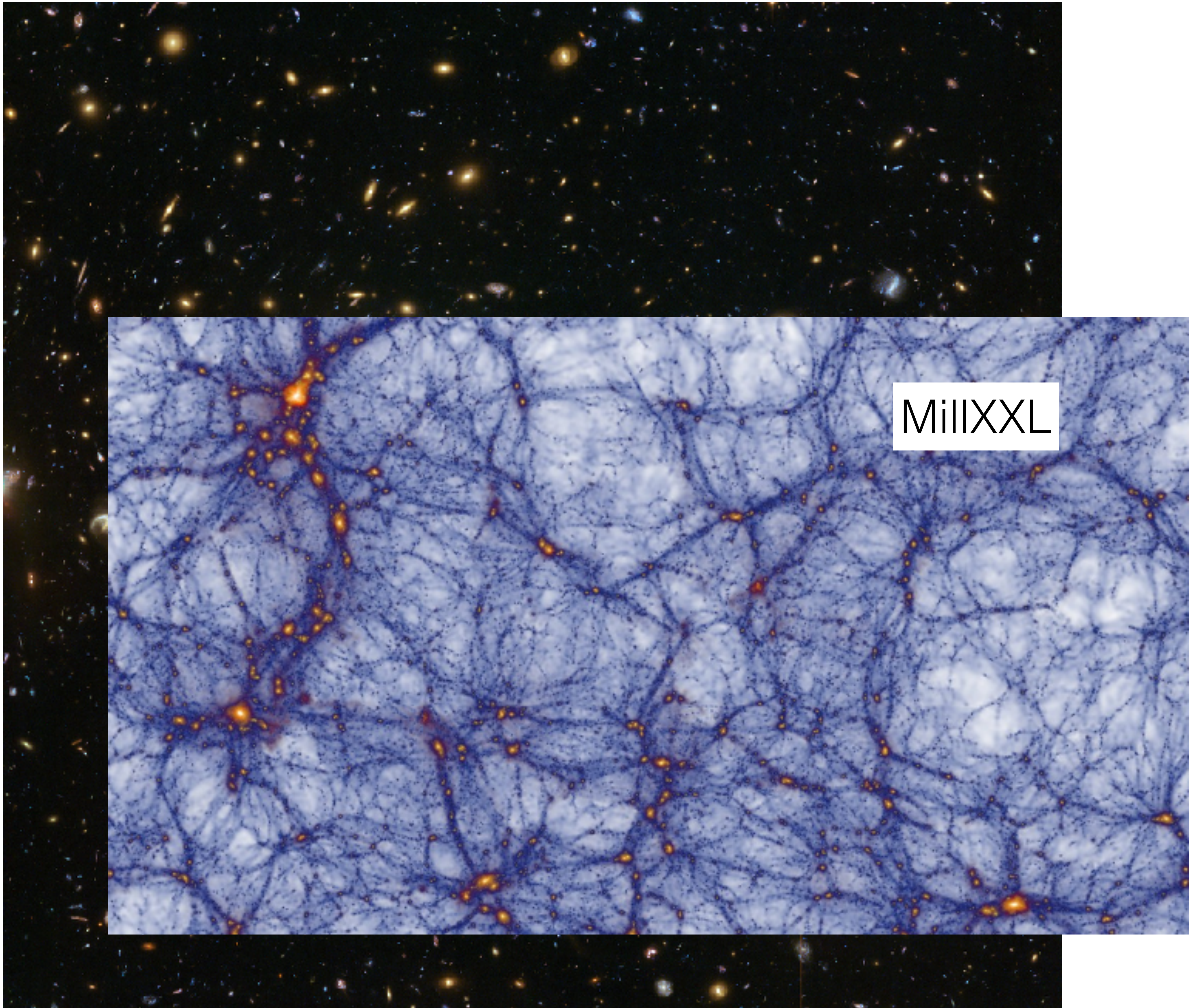




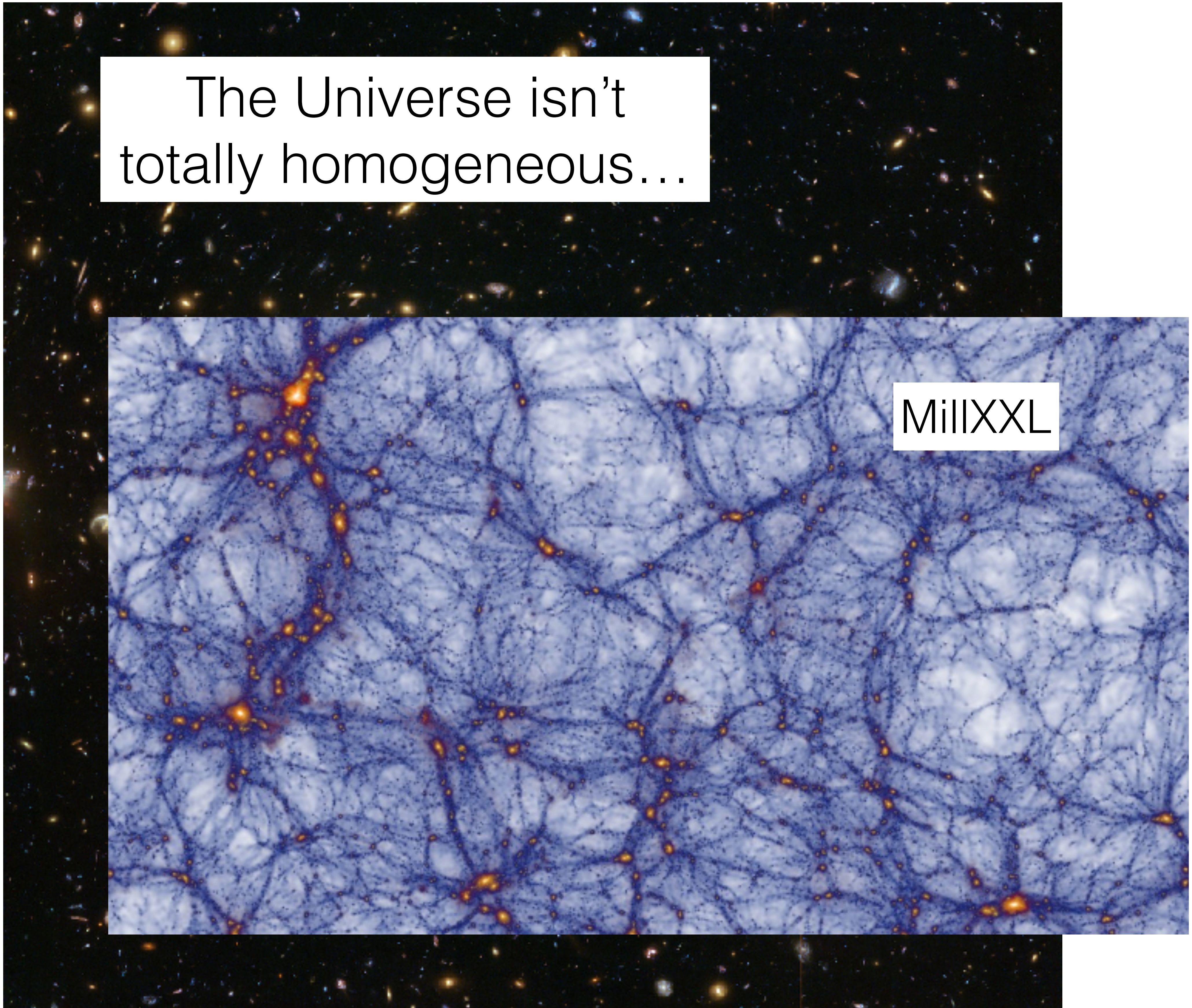




General consensus on energy budget of Universe


MillXXL

The Universe isn't totally homogeneous…

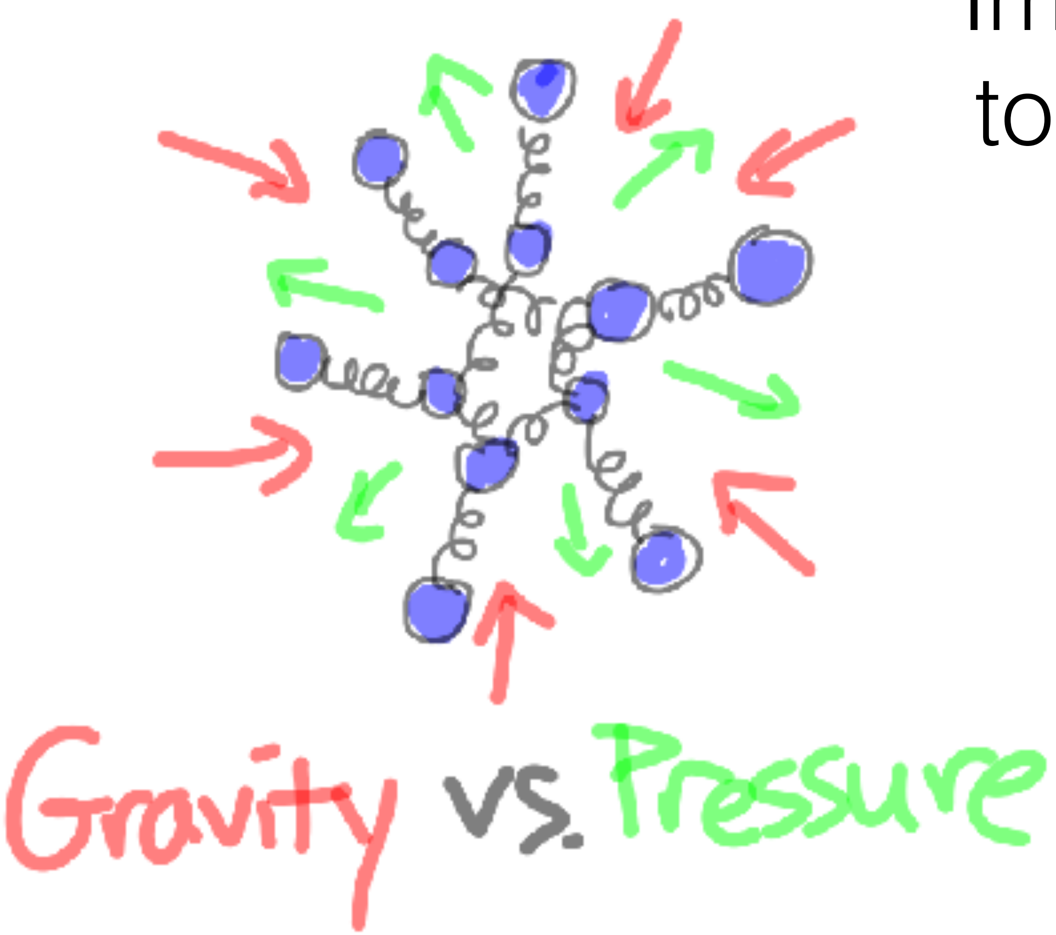


How does structure form?

What does it tell us about dark matter?

Loeb & Zaldarriaga

Basic physics that sets the scales of structure formation



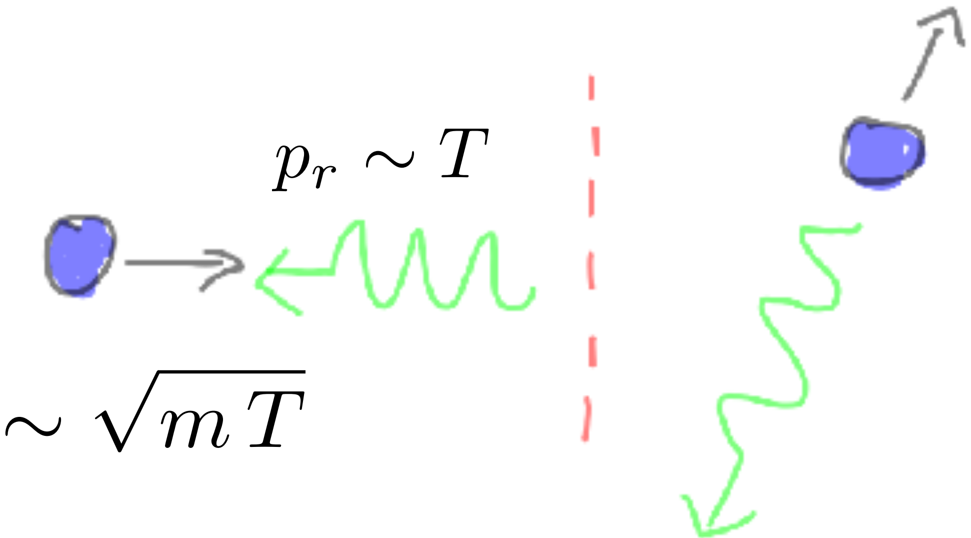
Imagine massive particles coupled to a light force (not gravity) carrier, i.e. radiation

e.g. baryon collapse resisted by photons

structure starts to form when no pressure (i.e. particles decouple from force carrier)

structures smaller than horizon size at decoupling are suppressed

What is decoupling scale?



$p_r \sim T$

$p_m \sim \sqrt{mT}$

$(\Delta p_m)_1 \sim p_r \sim T$

How many scatters for O(1) momentum change?

$$(\Delta p_m)_N \sim \sqrt{N}\,(\Delta p_m)_1 \sim \sqrt{N}T$$
$$\Rightarrow N \sim \frac{m}{T}$$

Compare rate for N scatters to Hubble

$$\frac{n_r\sigma}{N} \sim \frac{T}{m} n_r \sigma \sim \frac{T^4}{m}\sigma > H$$

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

Given $T_{\rm d}$ it's convenient to express a cutoff scale

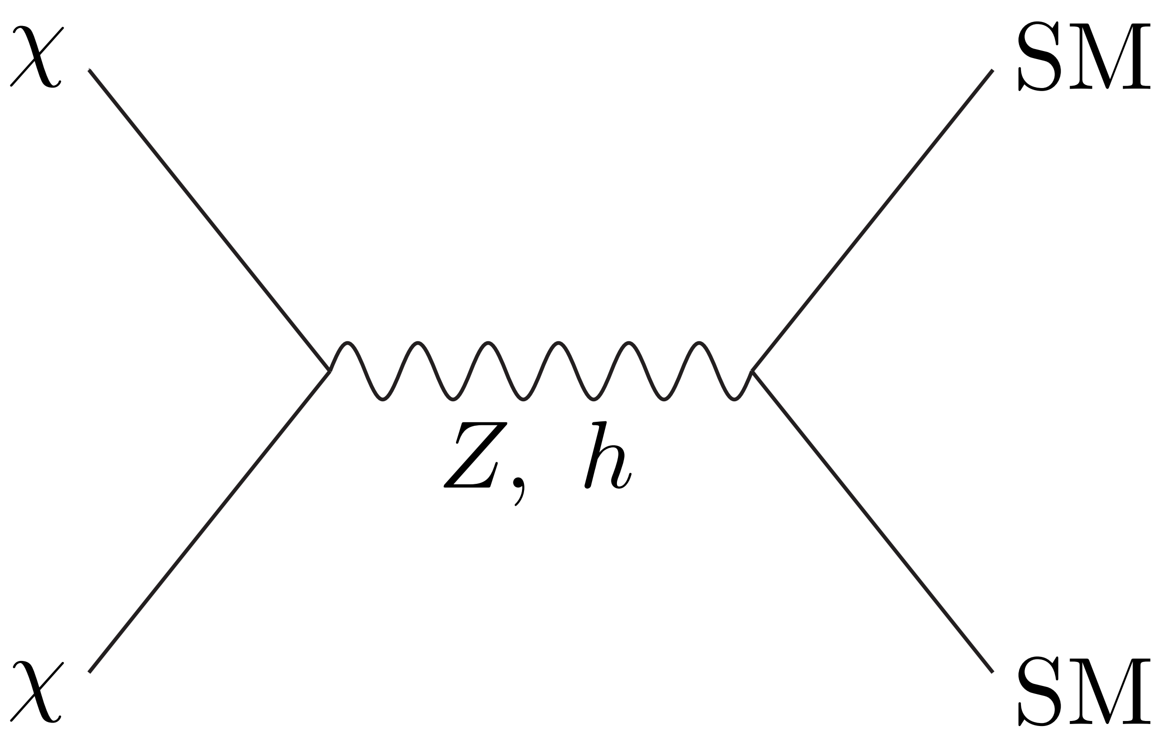
$$M_{\rm cut} = \rho_m \left(T_d\right) \frac{4\pi}{3} H_d^{-3} \sim 10^8 M_\odot \left(\frac{T_d}{\rm keV}\right)^{-3}$$

Structures smaller than this don't form

Weakly Interacting Massive Particle

Stable, uncharged particle χ with mass roughly

$$m_\chi \sim m_Z,\ m_W,\ m_h \sim 100\ \mathrm{GeV/c^2}$$



Common in extensions of the Standard Model, e.g. SUSY, extra dims., …

Often easy to get correct DM abundance today

What does structure tell us about WIMP DM?

What decoupling temperature/cutoff scale do we expect for a WIMP?

Recall decoupling temp. is determined by interaction strength of DM with radiation

$$T_{\rm d} = \left(\frac{\Lambda^4 m_\chi}{M_{\rm Pl}}\right)^{1/4} \quad \text{with} \quad \sigma = \frac{T^2}{\Lambda^4}$$

Recall decoupling temp. is determined by interaction strength of DM with radiation

$$T_{\rm d} = \left(\frac{\Lambda^4 m_\chi}{M_{\rm Pl}}\right)^{1/4} \quad \text{with} \quad \sigma = \frac{T^2}{\Lambda^4}$$

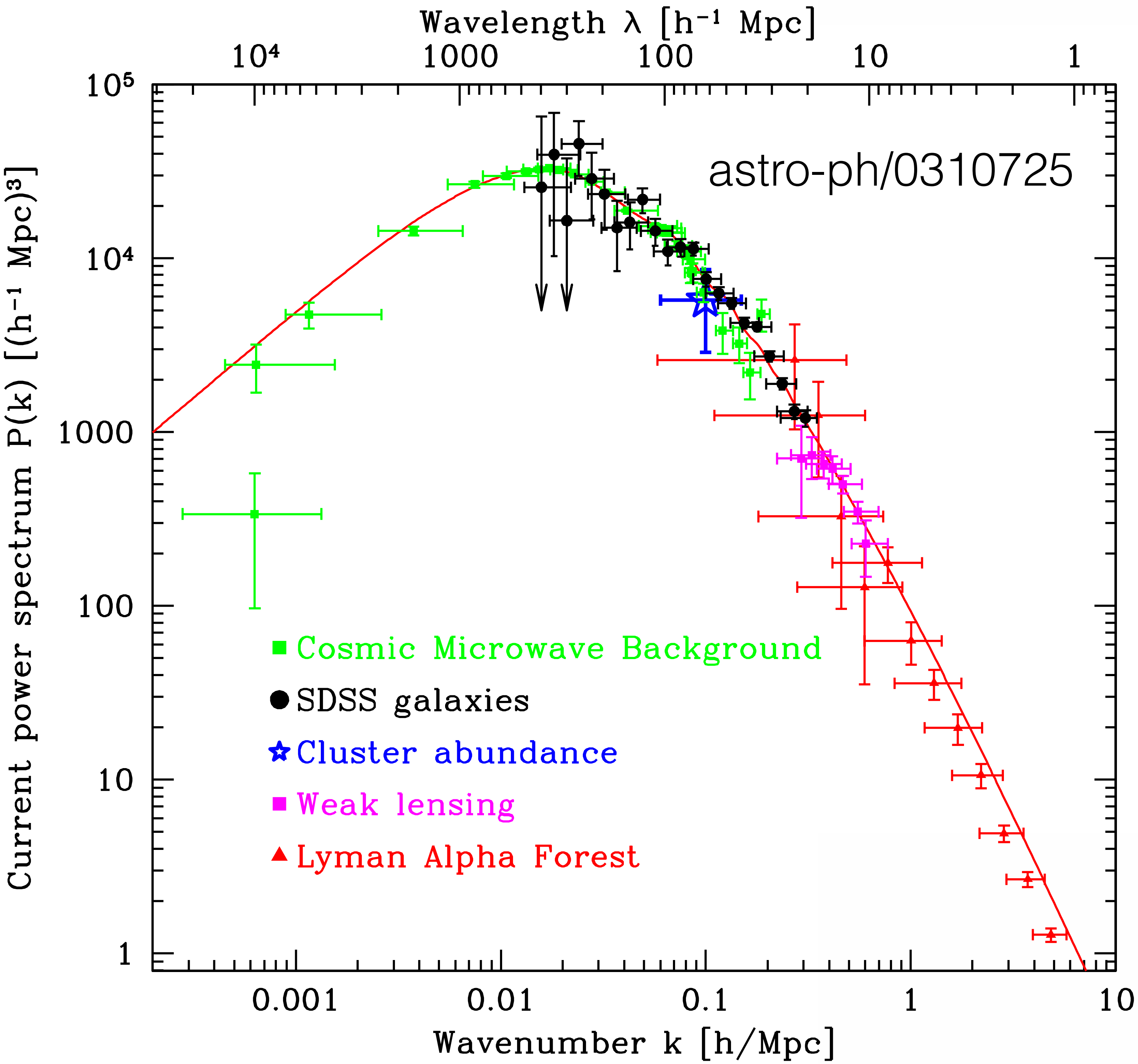
WIMP: ~100 GeV ➡ $T_{\rm d} \sim 10\ \mathrm{MeV}$

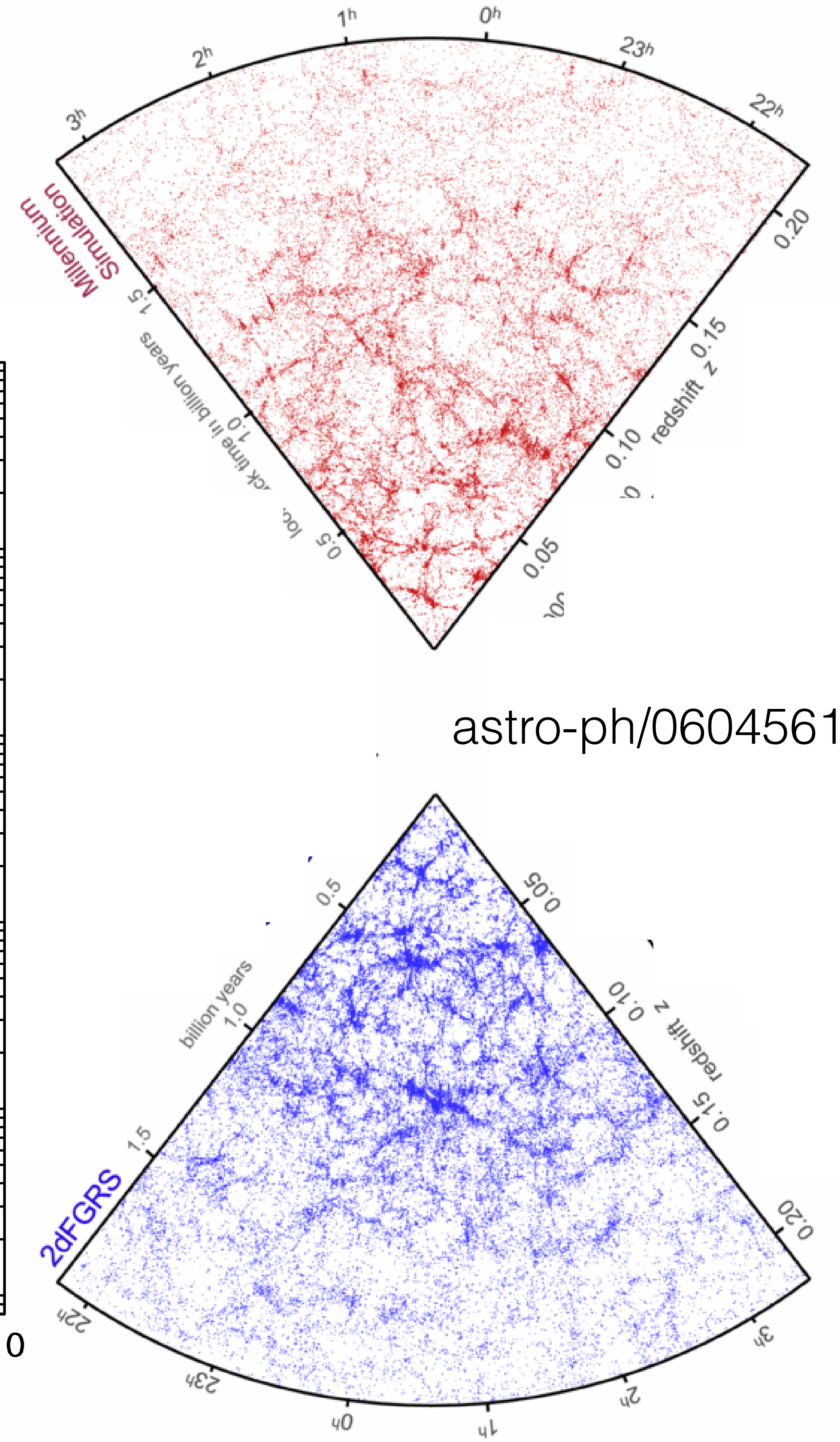
➡ $M_{\rm cut} \sim 10^8 M_\odot \left(\frac{T_d}{\mathrm{keV}}\right)^{-3} \ll M_\odot$

i.e. WIMP DM should behave as if non-interacting for structure down to smallest observable scales

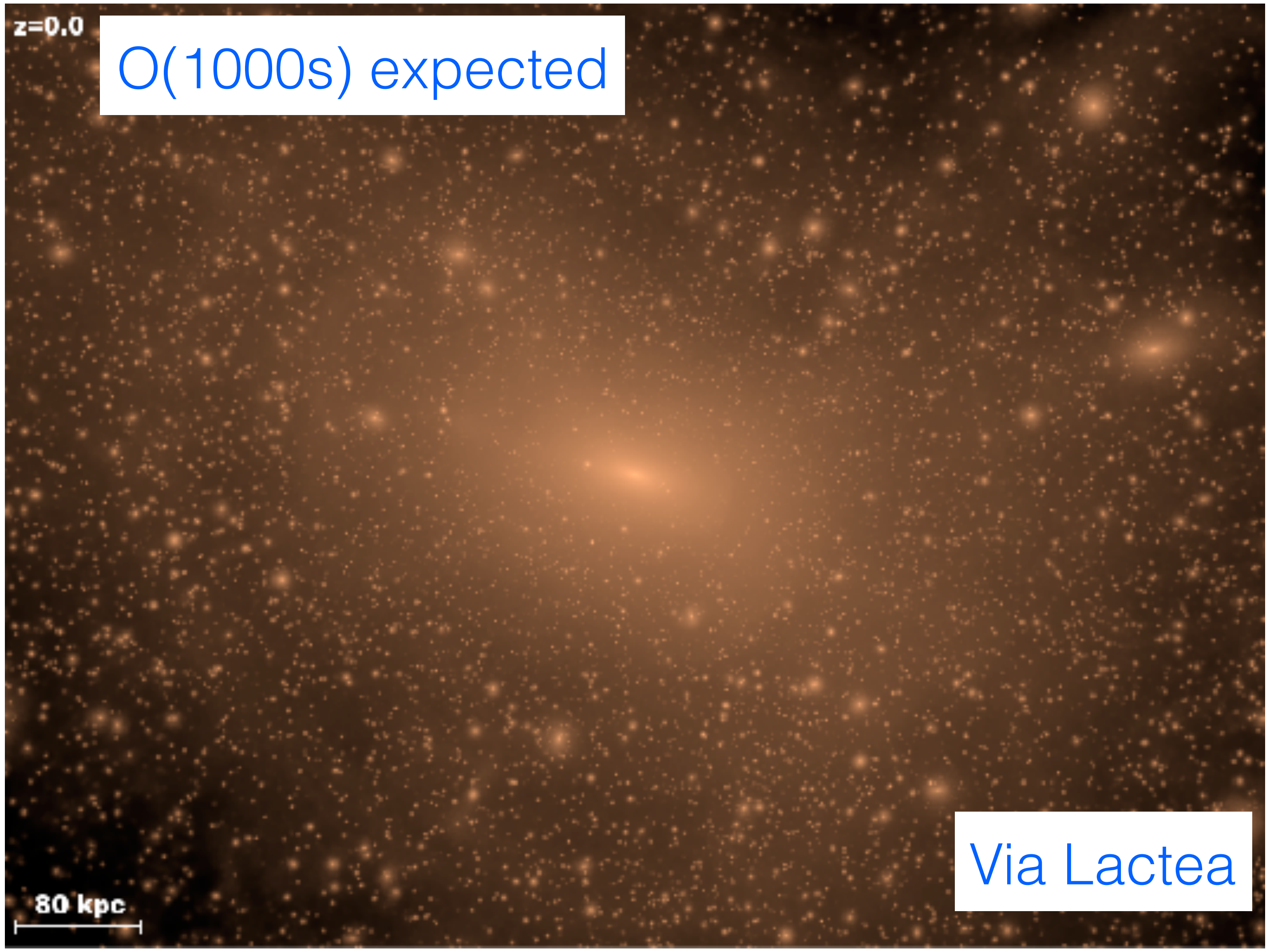
What does the data say?

Large Scales Look Good for WIMPs

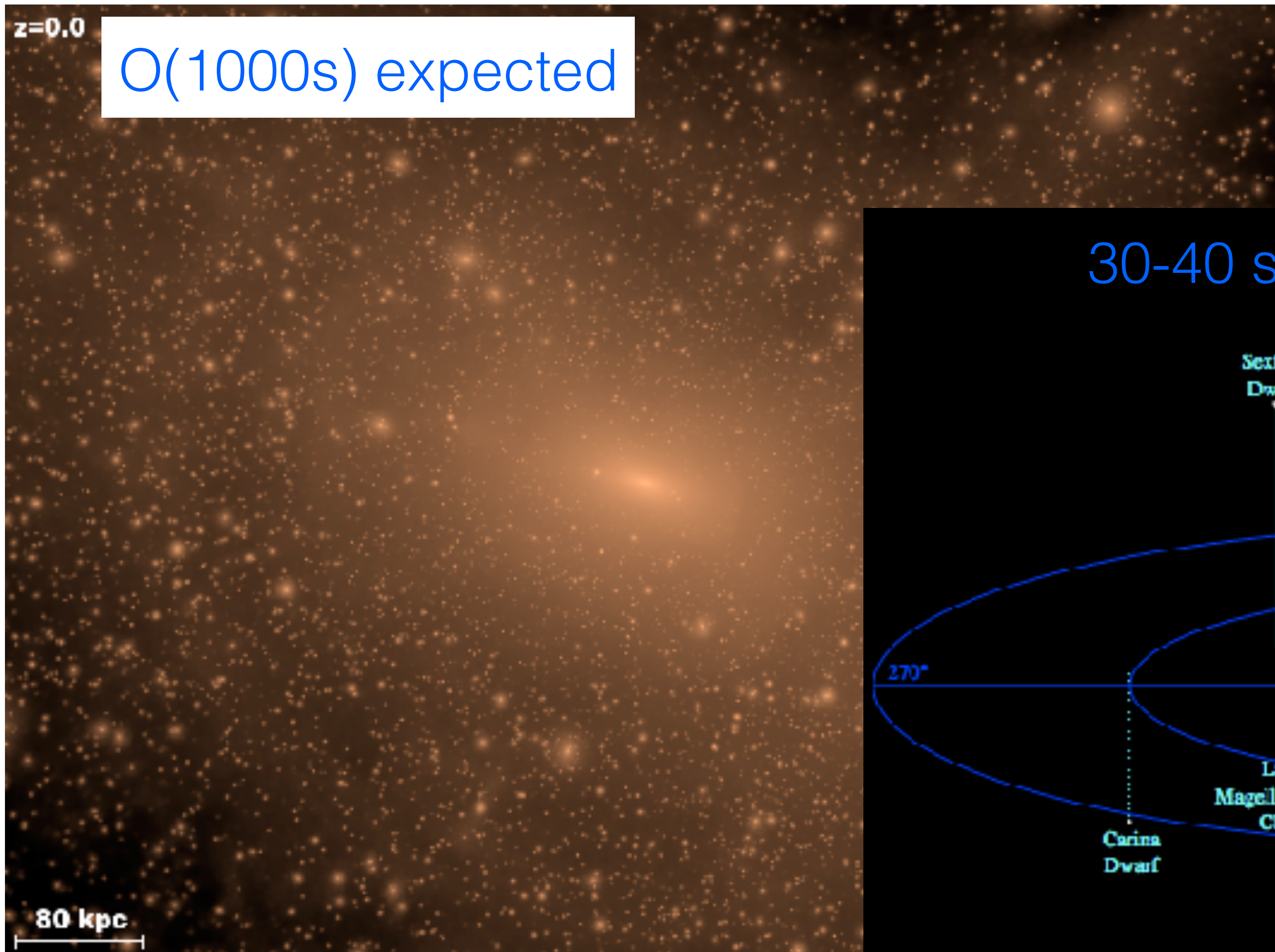


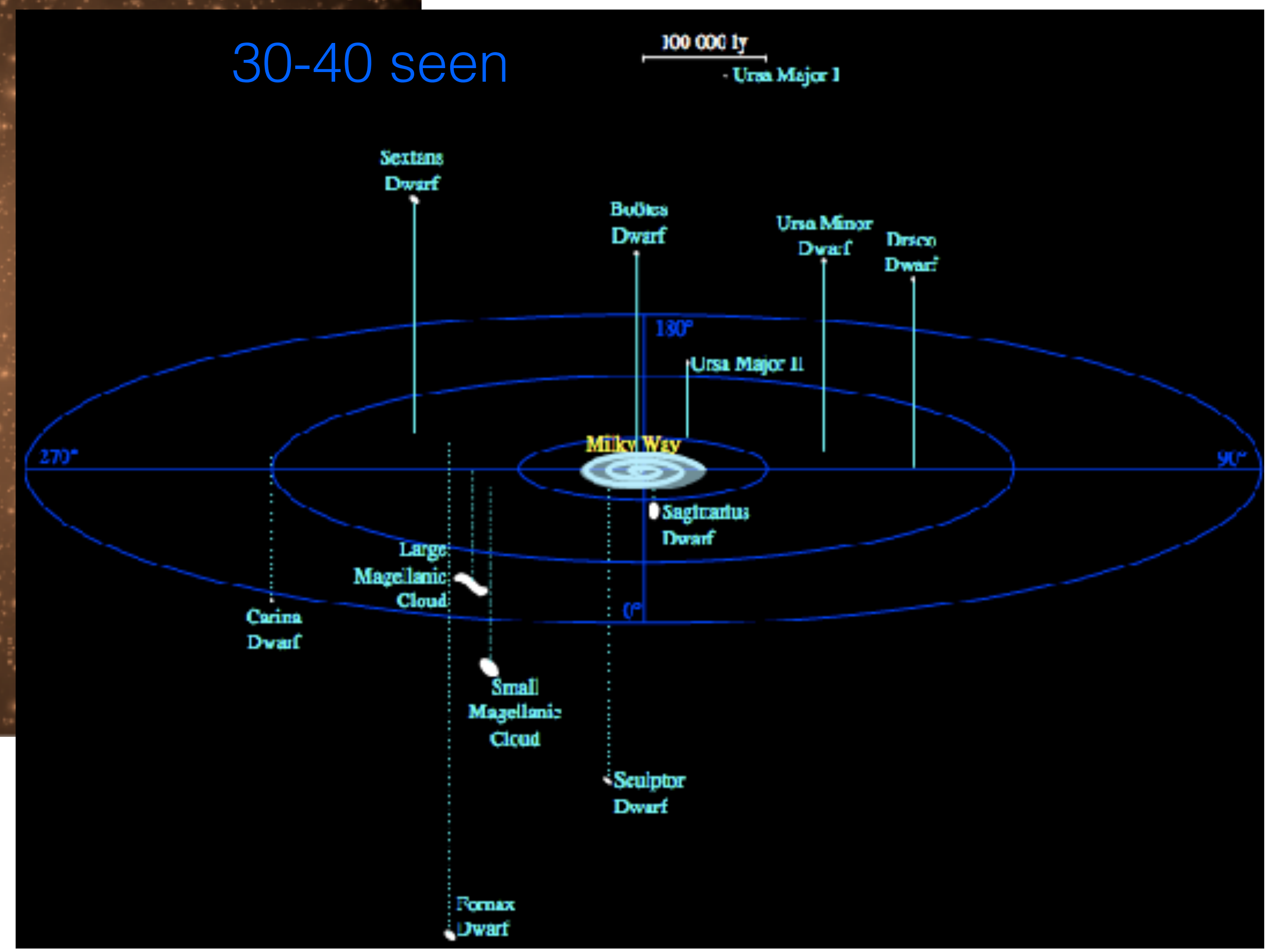


Count satellites of Milky Way-like galaxy



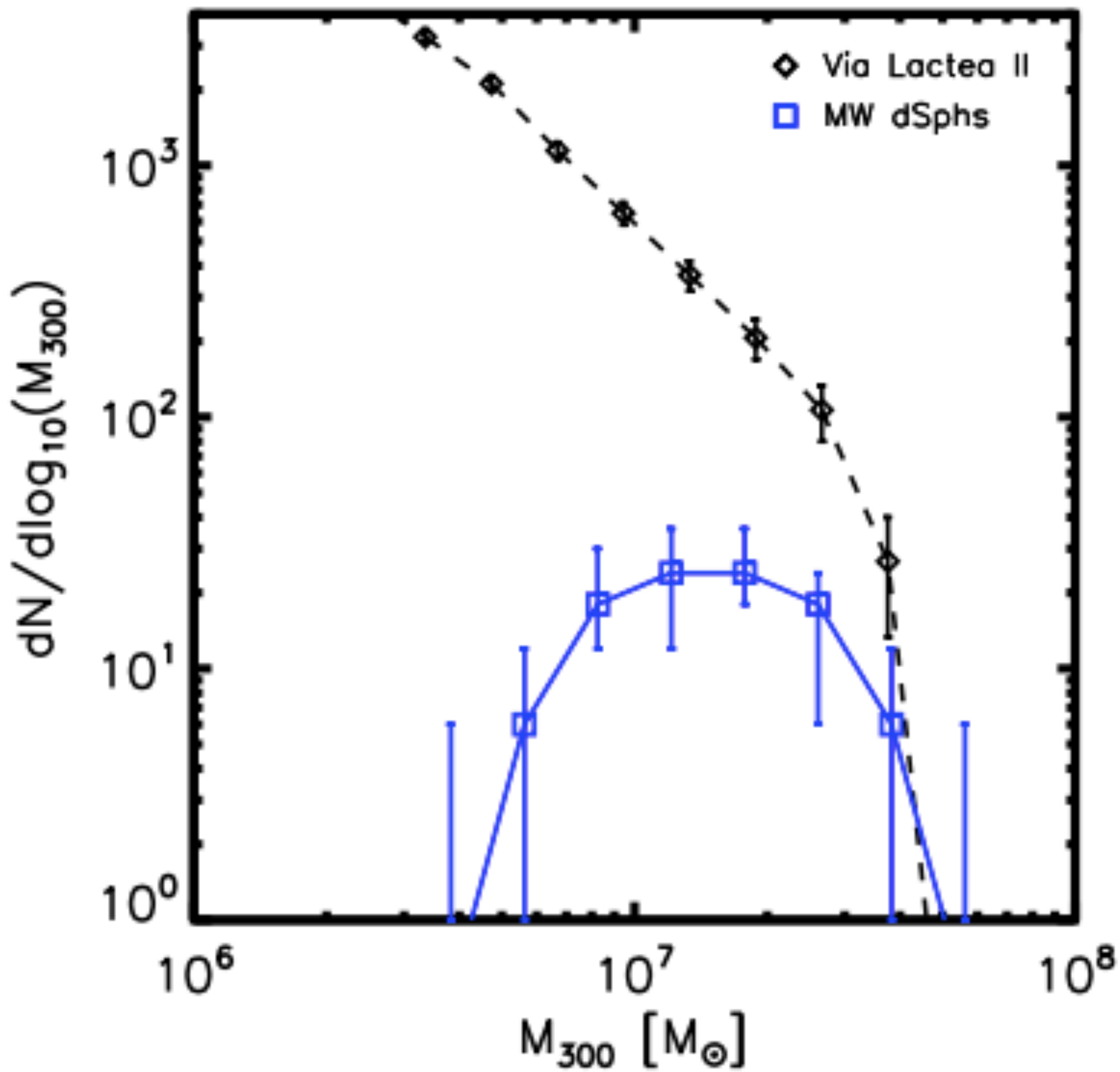
Count satellites of Milky Way-like galaxy





Count satellites of Milky Way galaxy

Bullock, arXiv:1009.4505



Compared to expectation, fewer small halos orbiting Milky Way-sized galaxy

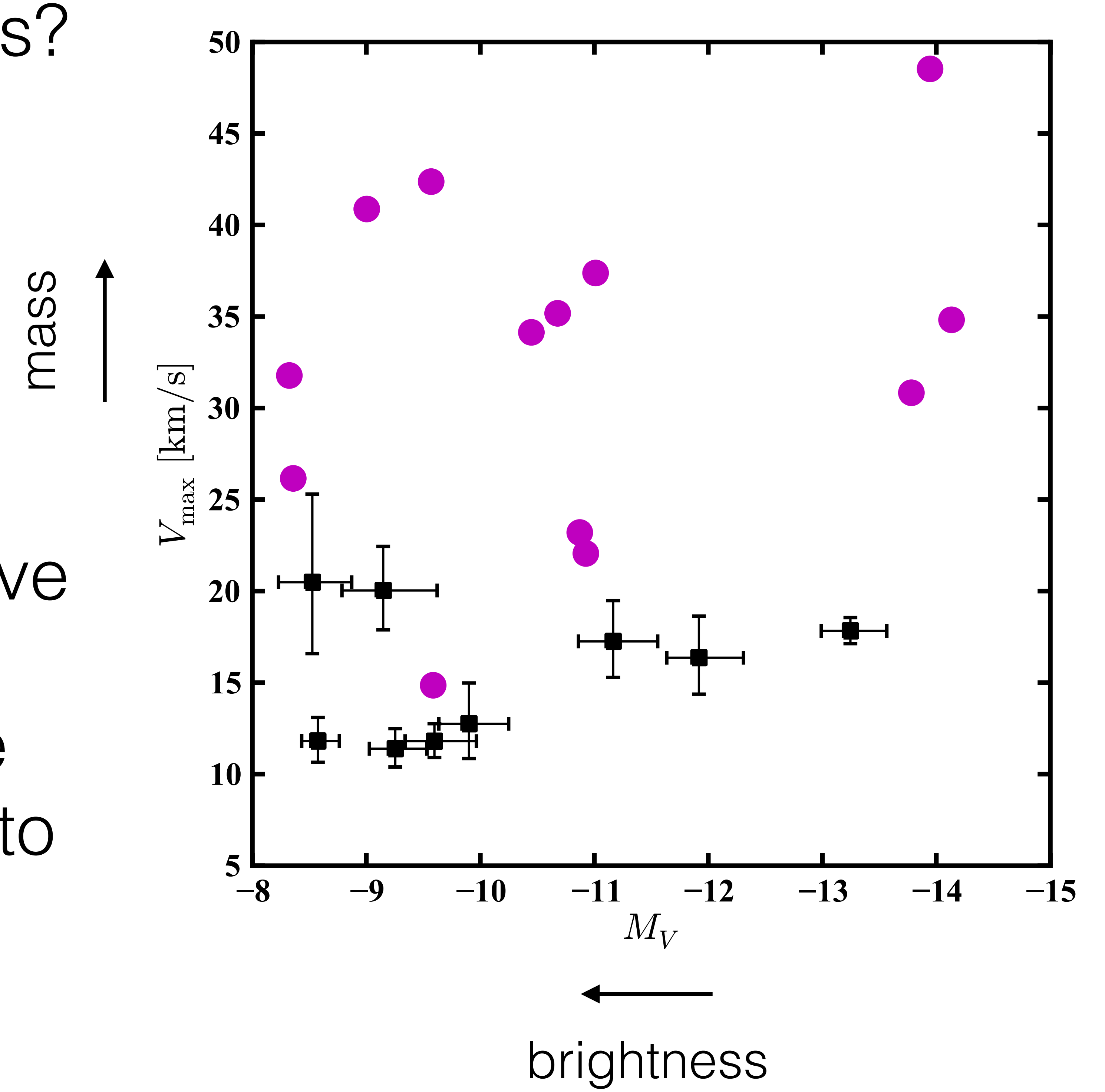
"Missing Satellites"

Suggestive of a cut off $M_{cut} \sim 10^{7-9}$ $M_\odot$, much larger than WIMP case

$T_d \sim 1$ keV

Boylan-Kolchin, Bullock, Kaplinghat, arXiv:1111.2048

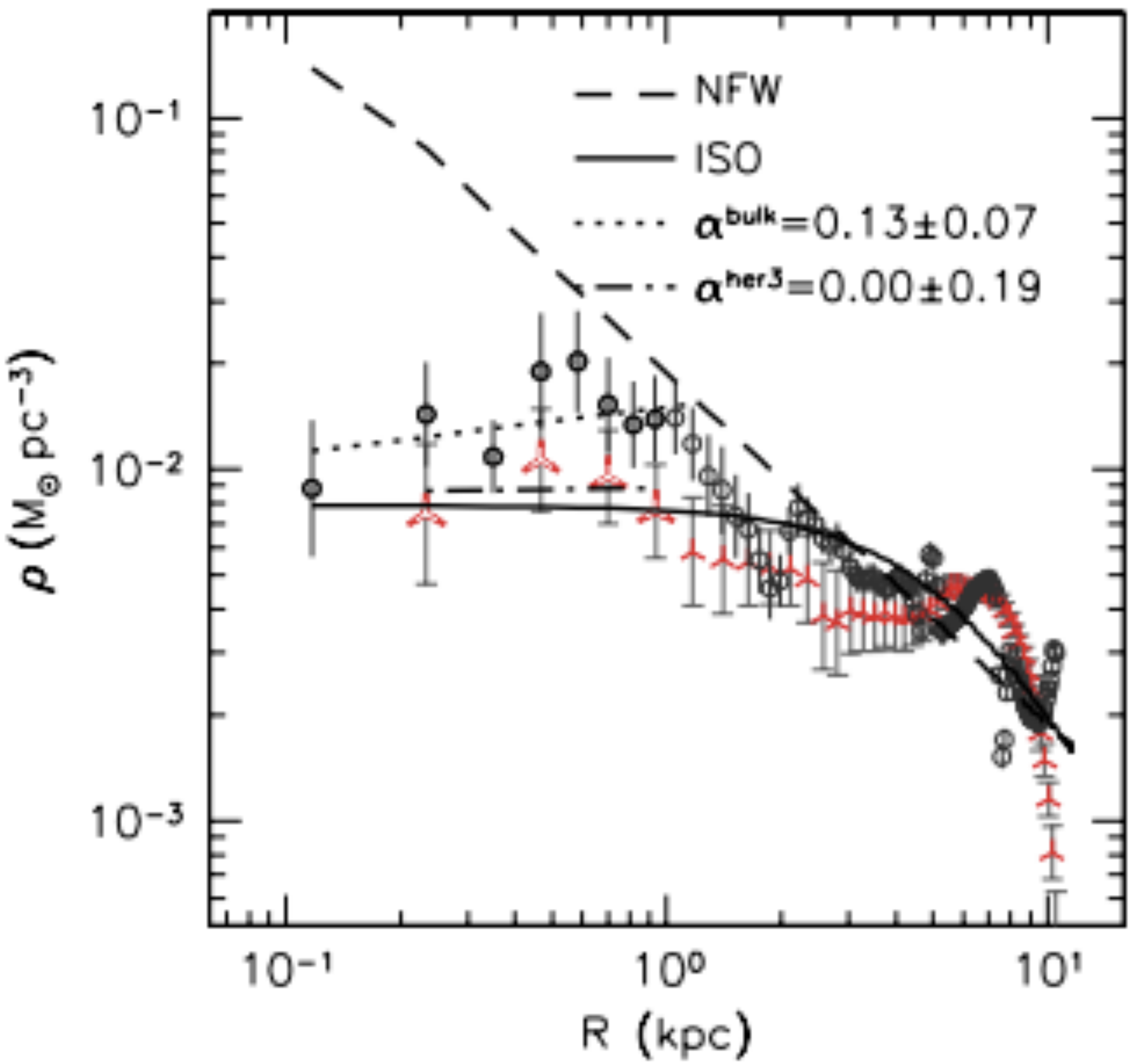
Could be selection bias?



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

"Too Big to Fail"

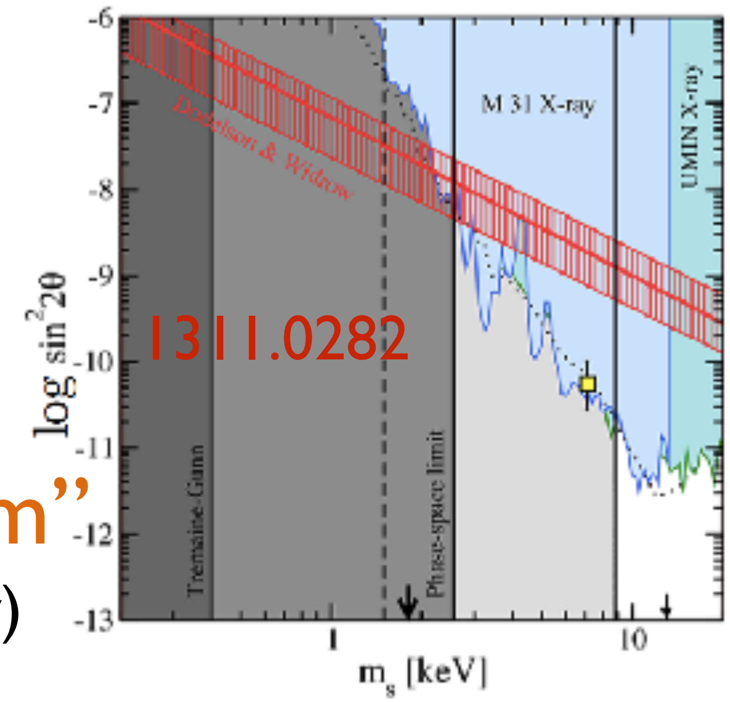
Oh *et al.*, arXiv:1011.0899



DM density profiles appear flatter, less cuspy at center than expected

“Core vs. Cusp”

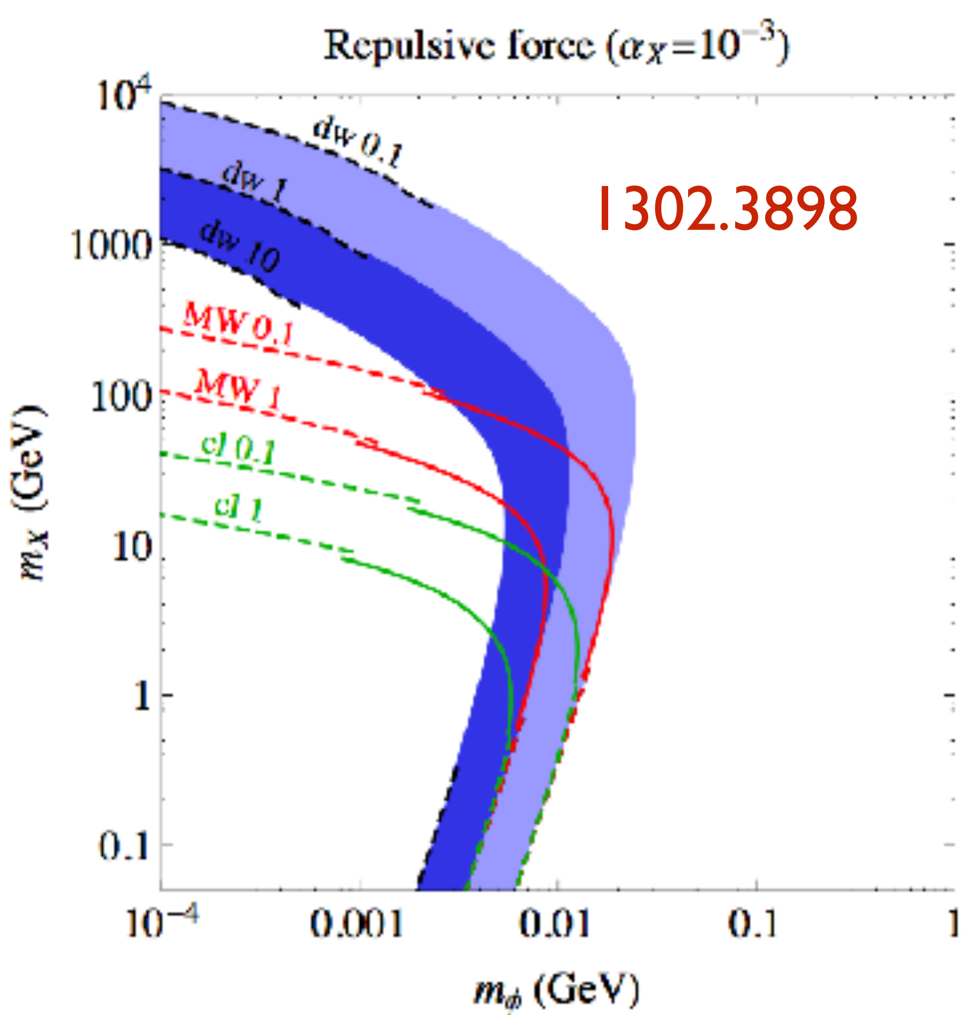
Potential Resolutions



1311.0282

Could be fixed by baryonic effects

(Brooks, Governato, Pontzen, ++)



1302.3898

DM could be "warm"

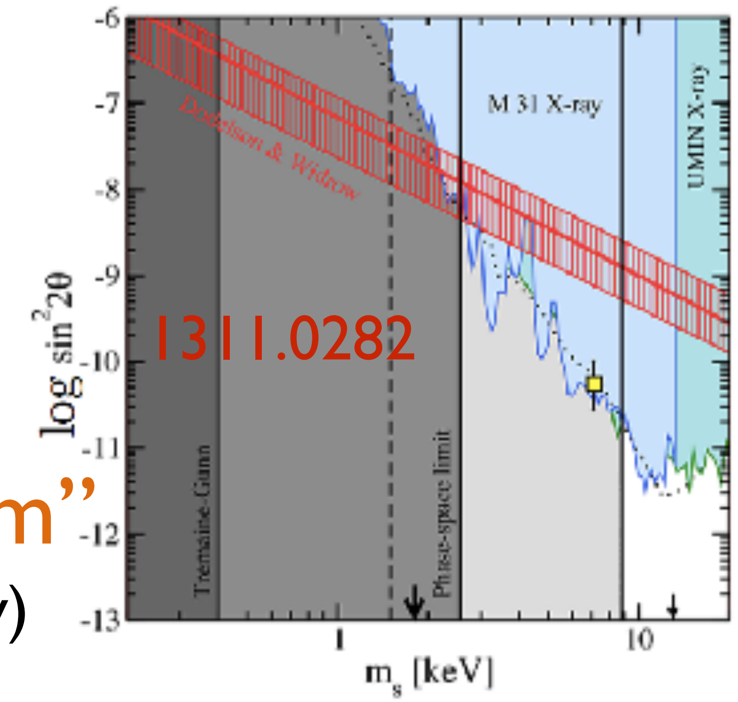
(See talk by O. Ruchayskiy)

DM could self-interact

(See talk by S. Tulin)

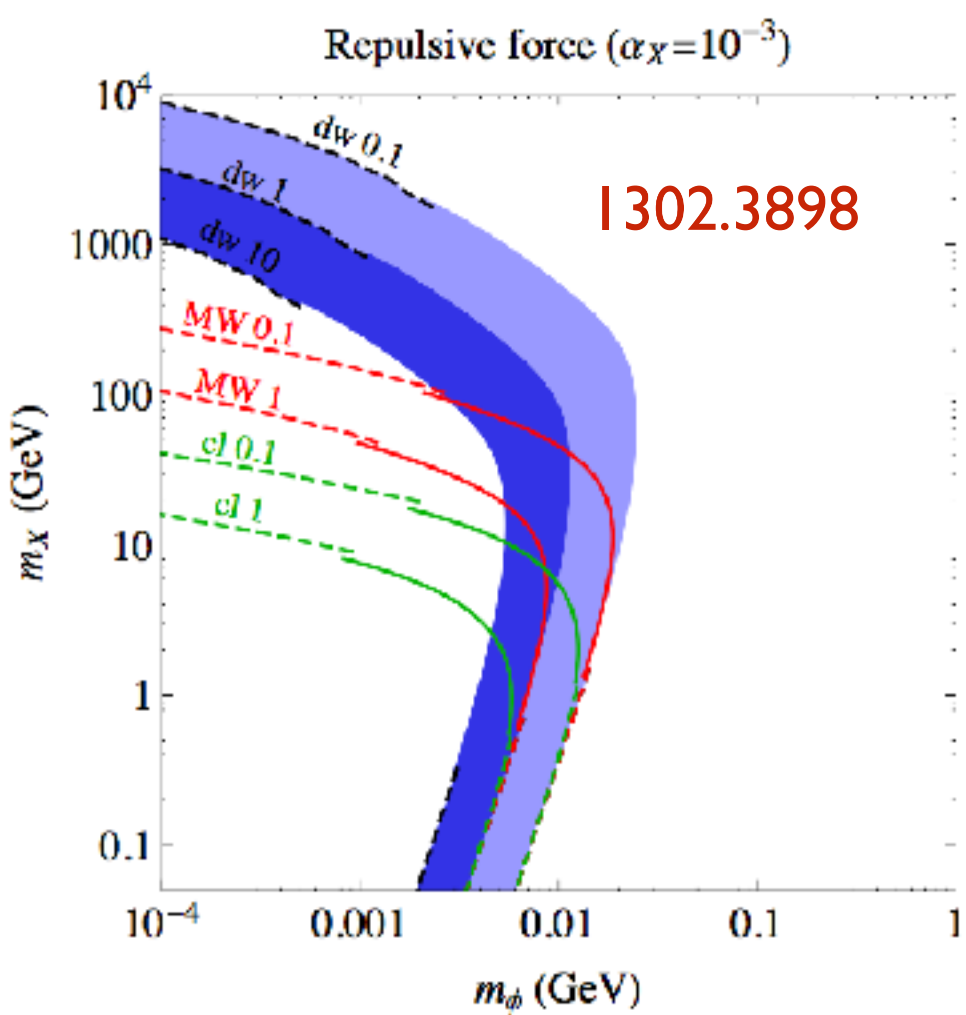
DM could interact with the "plasma"

Potential Resolutions



Could be fixed by baryonic effects

(Brooks, Governato, Pontzen, ++)



DM could be "warm"

(See talk by O. Ruchayskiy)

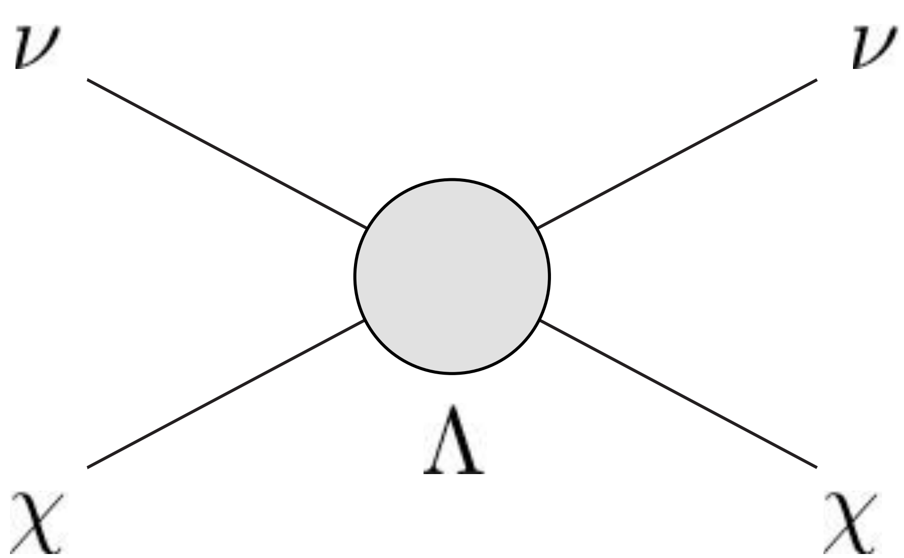
DM could self-interact

(See talk by S. Tulin)

DM could interact with the "plasma"

Boehm, et al.
Shoemaker, 1305.1936
van den Aarssen et al., 1205.5809
Hooper et al. 0704.2558

Recall $M_{\rm cut} \sim 10^8 M_\odot \left(\frac{T_{\rm d}}{\rm keV}\right)^{-3}$ so want $T_{\rm d} \sim {\rm keV}$



$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2}\bar{\nu}\nu\bar{\chi}\chi \Rightarrow \sigma = \frac{T^2}{\Lambda^4}$$

then $T_d \sim \left(\frac{\Lambda^4 m_\chi}{M_{\rm Pl}}\right)^{1/4} \sim {\rm keV}$

if $\Lambda^4 m_\chi \sim (100\ {\rm MeV})^5$

(Note: large annihilation cross section implies asymmetric DM)

EFT analysis highlights a small energy scale

Need to build a model!

Model Building at Low Energy Scales

Standard Model symmetries

$$SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_{\rm em}$$

Standard Model particle content

$$\left.\begin{array}{ll} \ell = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} & e_R \\ & \\ q = \begin{pmatrix} u_L \\ d_L \end{pmatrix} & u_R \;\; d_R \end{array}\right\} \times 3$$

$$H = \begin{pmatrix} \rho^+ \\ v + h + \rho^0 \end{pmatrix} \qquad G^a_\mu,\ W^b_\mu,\ B_\mu \to G^a_\mu,\ A_\mu$$

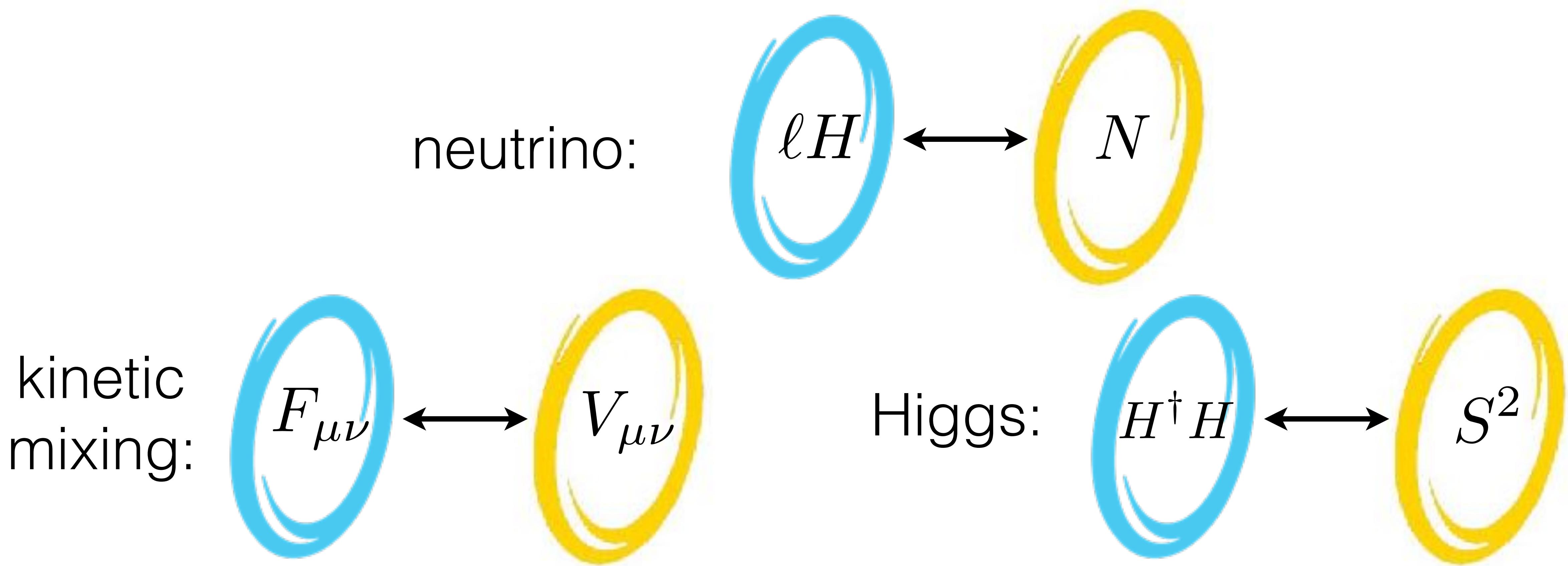
Renormalization: lower dim. operators (fewer fields/particles) more important

Model Building at Low Energy Scales

Standard Model symmetries $SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_{\rm em}$

Portals: coupling via stuff uncharged w.r.t. SM

Lead to minimal difficulties incorporating hidden sectors

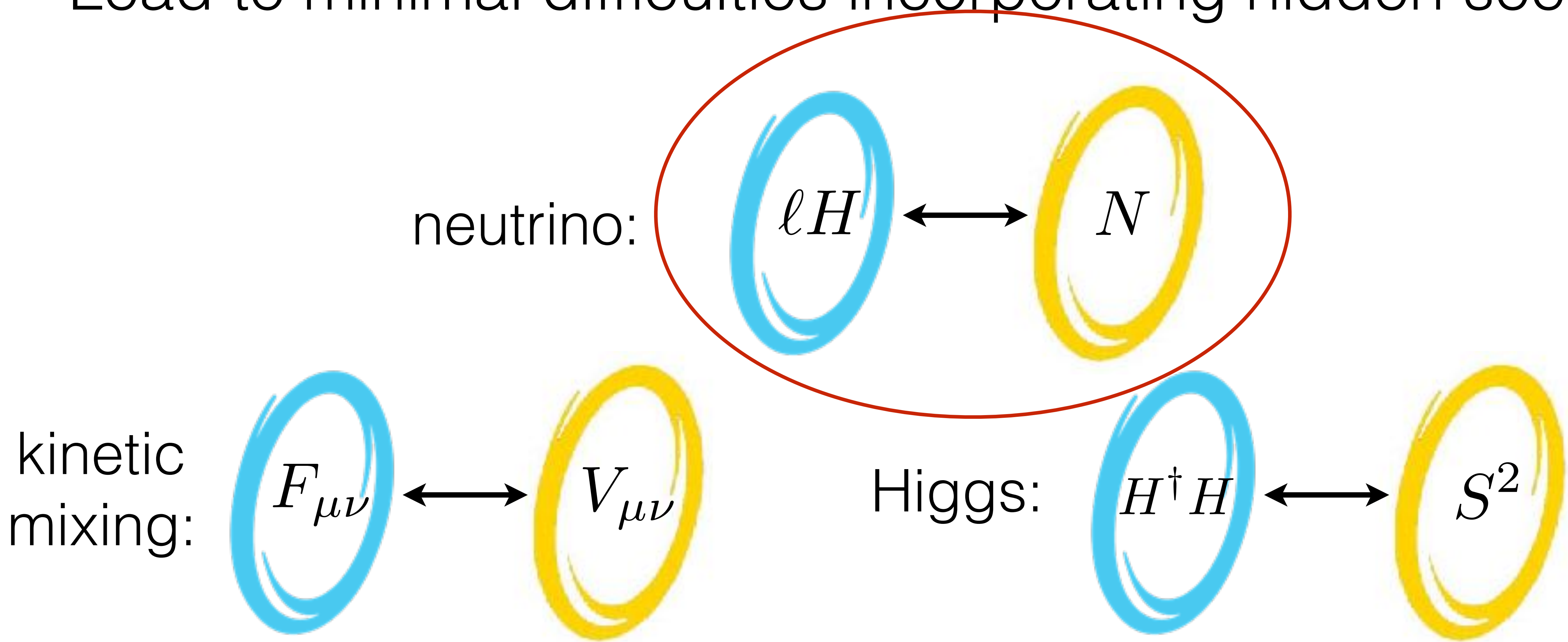


Model Building at Low Energy Scales

Standard Model symmetries $SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_{\rm em}$

Portals: coupling via stuff uncharged w.r.t. SM

Lead to minimal difficulties incorporating hidden sectors

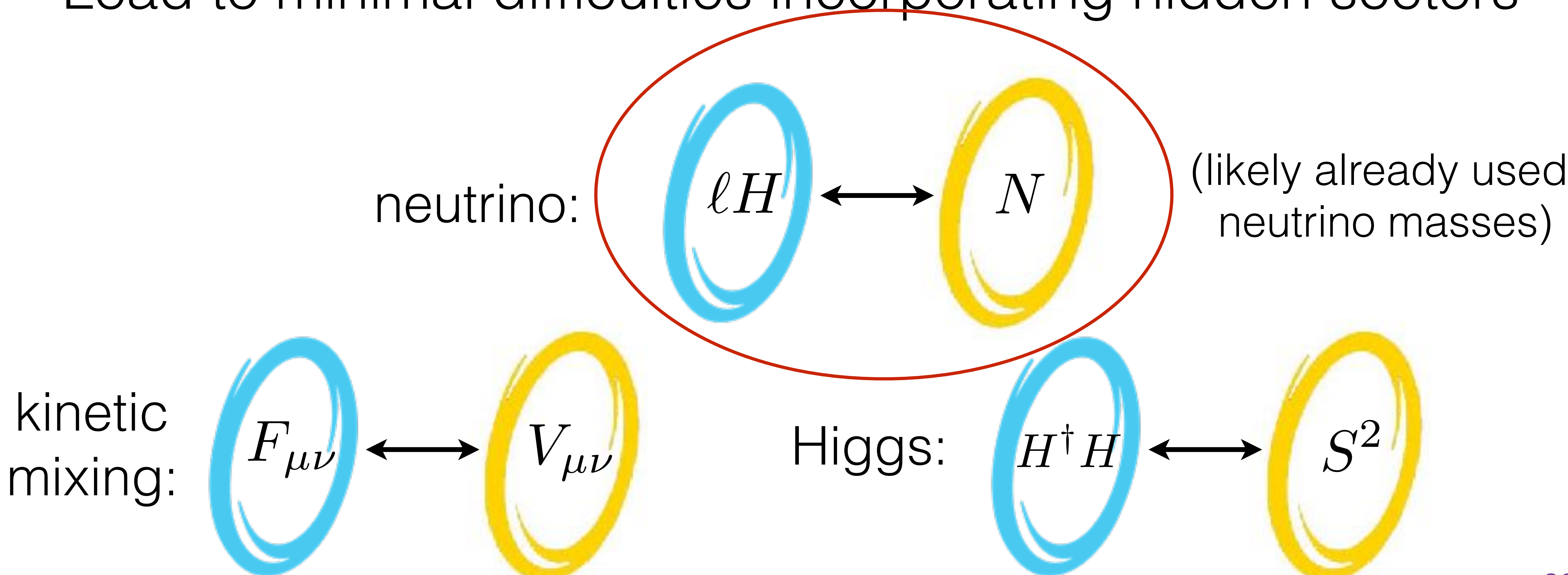


Model Building at Low Energy Scales

Standard Model symmetries $SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_{\rm em}$

Portals: coupling via stuff uncharged w.r.t. SM

Lead to minimal difficulties incorporating hidden sectors



Minimal Model

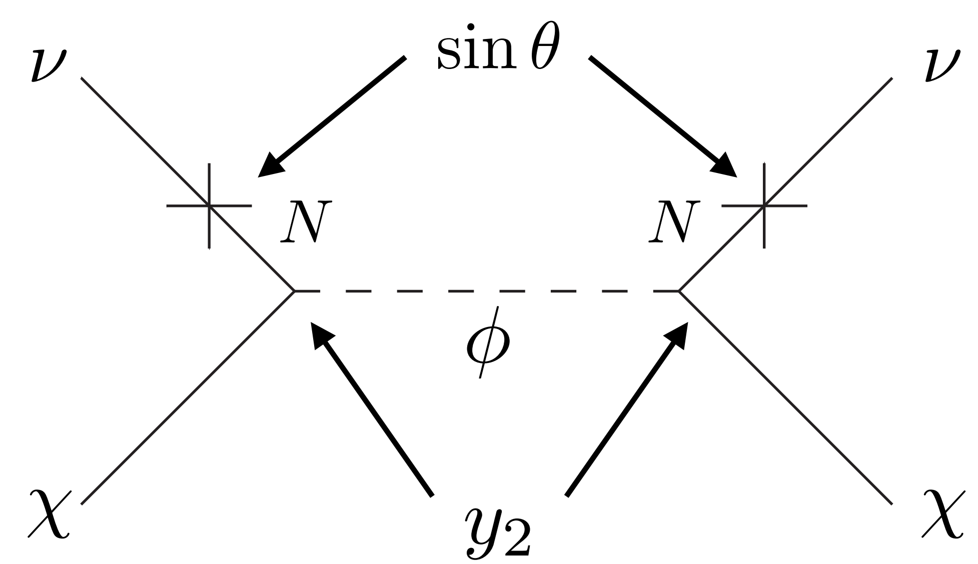
Simply coupling DM to the "neutrino portal" $\ell H \chi$ leads to DM decay

Can avoid with 2 new particles N, ϕ

χ and ϕ have (opposite) "dark charge"

$$\mathcal{L} \supset -\frac{m_{ij}}{v^2}\left(H\ell_i\right)\left(H\ell_j\right) - \underbrace{M N_1 N_2 - \lambda_i N_1 H \ell_i - y_1 \phi^* N_1 \chi - y_2 \phi N_2 \chi}_{\text{lepton number conserved (for small v masses \& large mixing)}} + \text{h.c.}$$

Effective neutrino-DM interaction generated



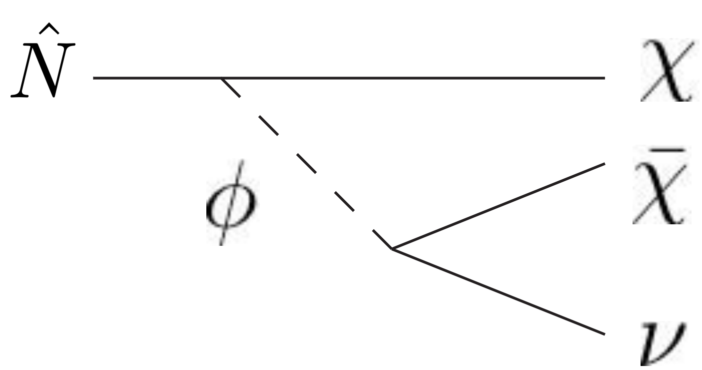
See talk by B. Batell

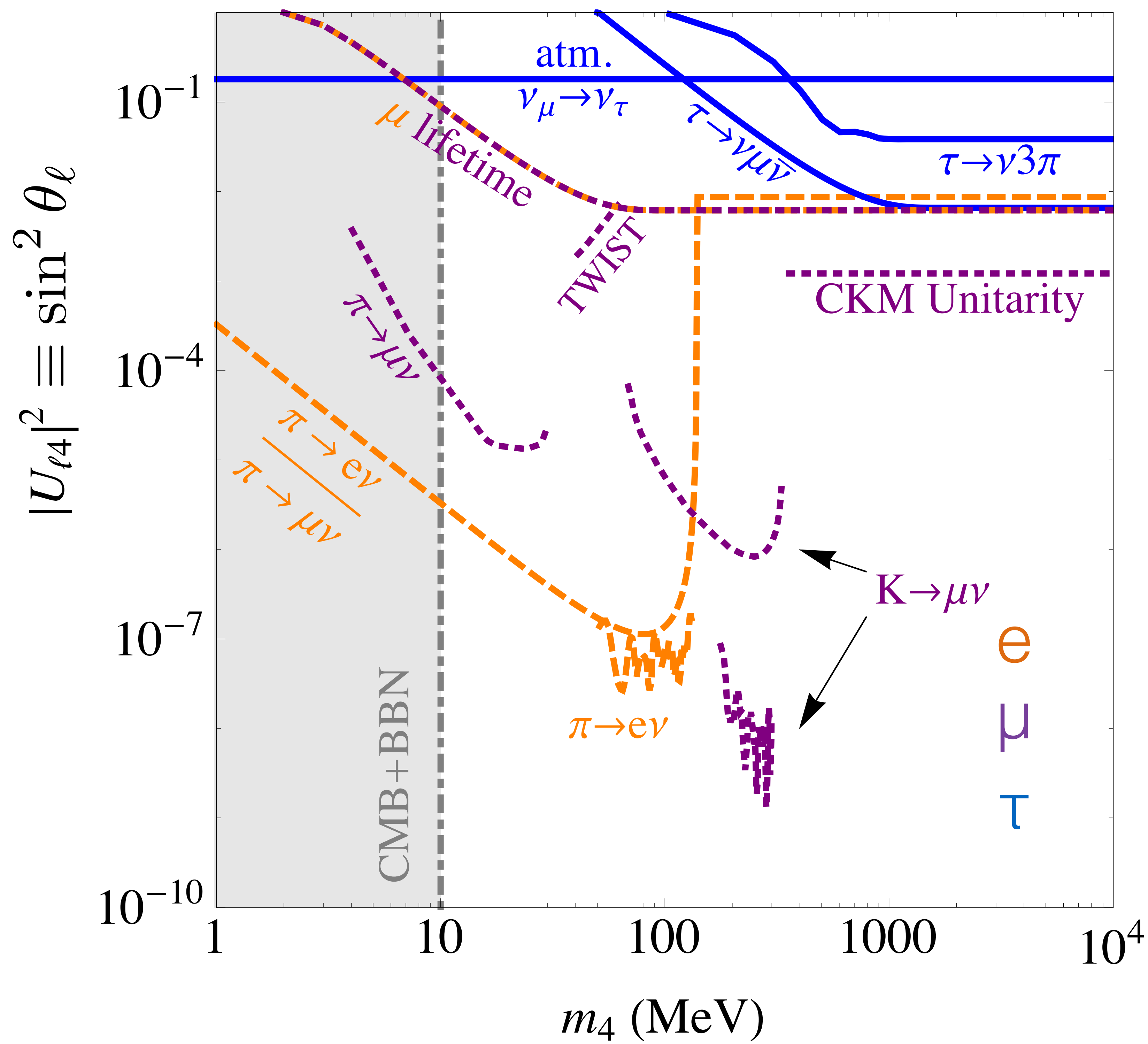
DM coupling to each neutrino flavor determined by mixing angle with sterile neutrino

Mixing angle affects known known neutrino properties

Strong limits on e, μ single out mixing with τ as promising

[Note: heavy (mostly sterile) ν decays invisibly]



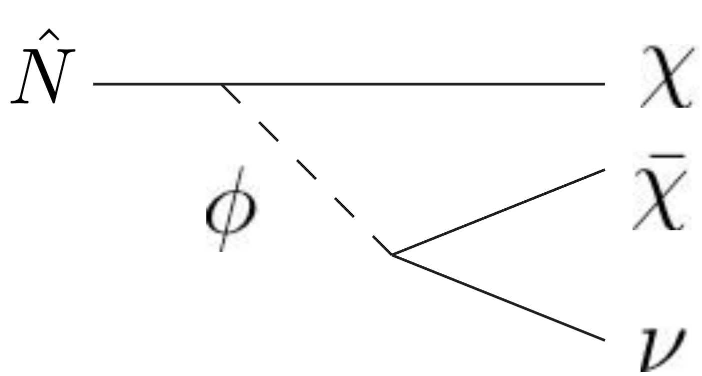


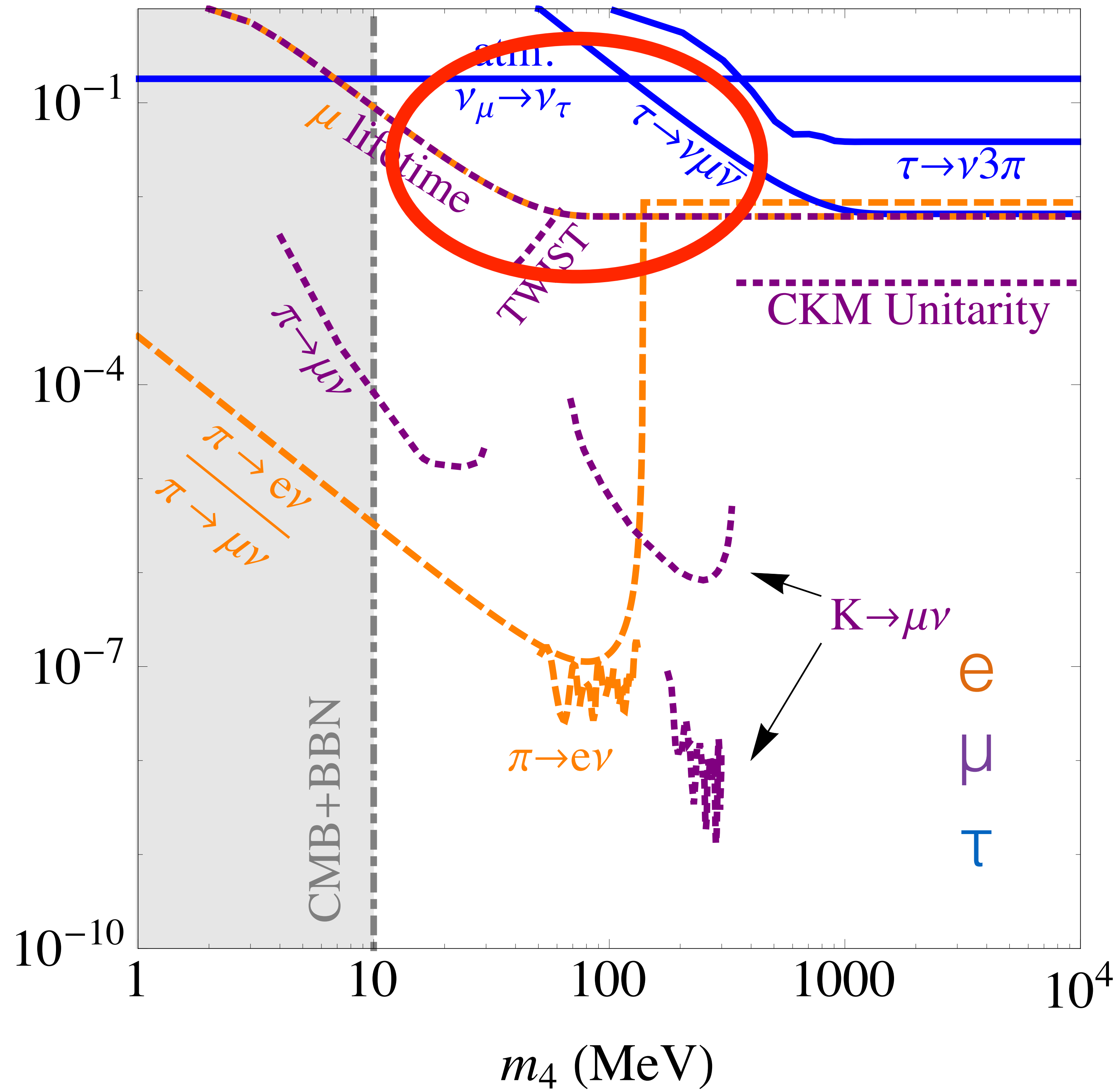
DM coupling to each neutrino flavor determined by mixing angle with sterile neutrino

Mixing angle affects known known neutrino properties

Strong limits on e, μ single out mixing with τ as promising

[Note: heavy (mostly sterile) ν decays invisibly]





Neutrino Oscillations

Assume mixing is dominantly with τ, just 1 more mixing angle in addition to the usual 3, and just 1 more (large) mass splitting

$$U = \begin{pmatrix} U_{e1}^{3\times3} & U_{e2}^{3\times3} & U_{e3}^{3\times3} & 0 \\ U_{\mu1}^{3\times3} & U_{\mu2}^{3\times3} & U_{\mu3}^{3\times3} & 0 \\ c_\theta U_{\tau1}^{3\times3} & c_\theta U_{\tau2}^{3\times3} & c_\theta U_{\tau3}^{3\times3} & s_\theta \\ -s_\theta U_{\tau1}^{3\times3} & -s_\theta U_{\tau2}^{3\times3} & -s_\theta U_{\tau3}^{3\times3} & c_\theta \end{pmatrix}$$

$|U_{e2}|^2, |U_{\mu2}|^2 + |U_{\tau2}|^2$ solar neutrinos $\Rightarrow$ Solar neutrinos potentially sensitive

$|U_{e1}|^2 \, |U_{e2}|^2$ KamLAND

$|U_{\mu3}|^2 \left(1 - |U_{\mu3}|^2\right)$ atmospheric/accelerator

$|U_{e3}|^2 \left(1 - |U_{e3}|^2\right)$ short baseline reactors

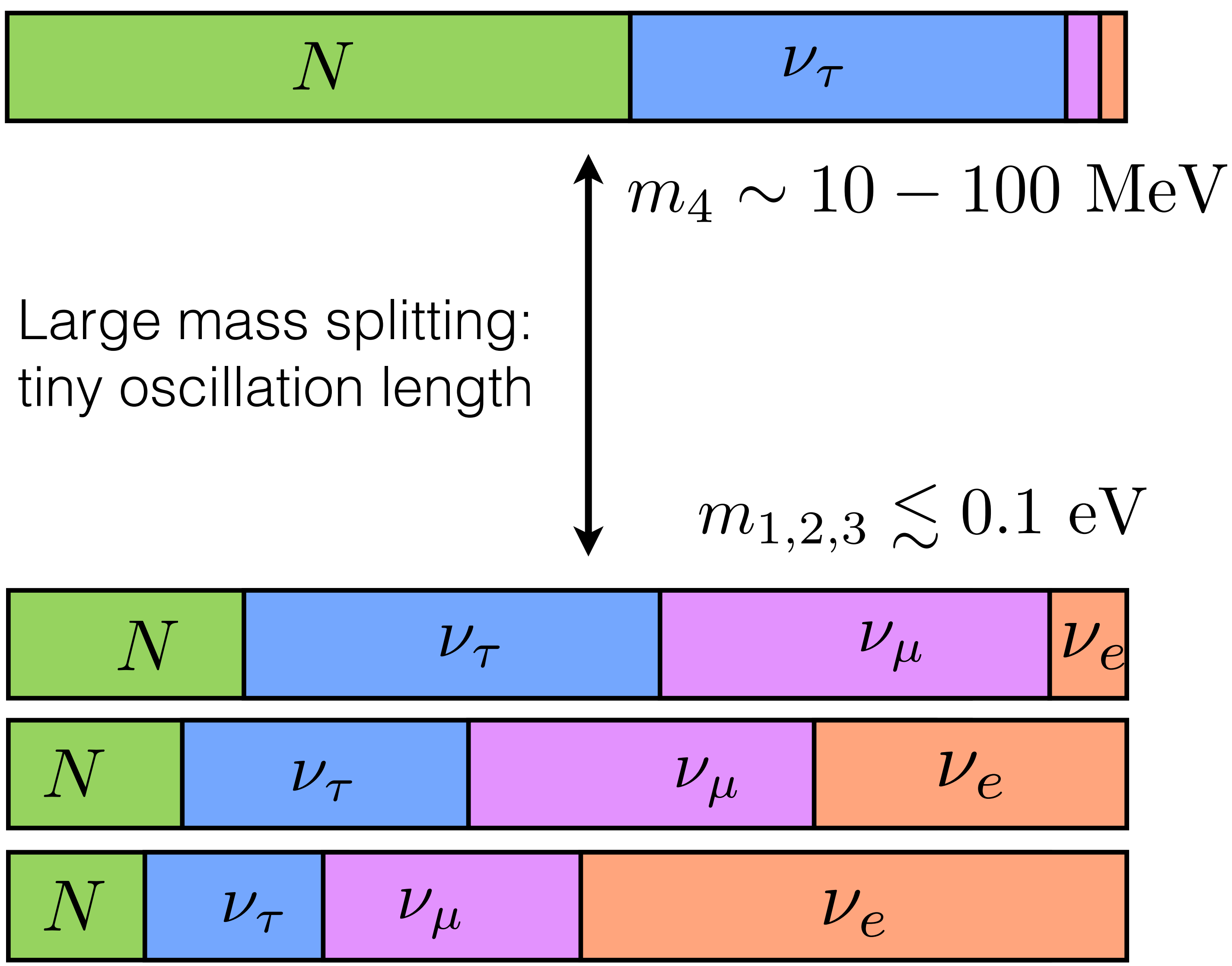
$|U_{e3}|^2 \, |U_{\mu3}|^2$ long baseline accelerator

Uncertainty on flux (^{8}B)~15%

$\sin\theta_\tau < 0.6$

Neutrino Oscillations

Assume mixing is dominantly with τ, just 1 more mixing angle in addition to the usual 3, and just 1 more (large) mass splitting



Light states admixtures of $\nu_e,\ \nu_\mu,\ \nu_{\tau N} = c_\theta \nu_\tau + s_\theta N$ with usual solar/atmos. splitting

$$\Delta m^2_\odot \simeq 7.5 \times 10^{-5}\ \text{eV}^2$$

$$\Delta m^2_{\text{atm}} \simeq 2.5 \times 10^{-3}\ \text{eV}^2$$

$\theta_{12},\ \theta_{13},\ \theta_{23}$
little affected by θ_τ

Atmospheric Neutrino Oscillations

$\nu_\mu,\ \nu_{\tau N}$ Hamiltonian:

$$H = \left(\frac{\Delta m^2}{4E}\right)\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \begin{pmatrix} V_\mu & 0 \\ 0 & V_{\tau N} \end{pmatrix}$$

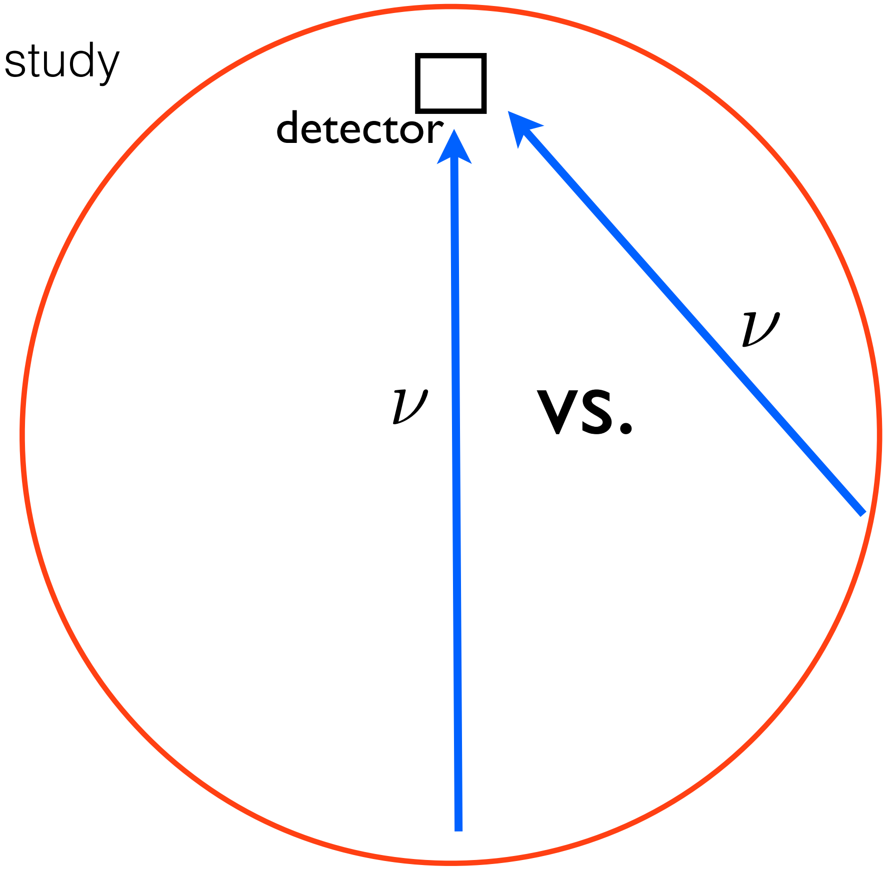
$$V_\mu = -\frac{G_F}{\sqrt{2}} n_n \sim \frac{1}{4000\ \mathrm{km}}$$

$$V_{\tau N} = -\frac{G_F}{\sqrt{2}} n_n \cos\theta_\tau$$

[Non-standard int.

$$\epsilon_{\tau\tau} = \frac{1}{6}\left(\frac{V_{\tau N}}{V_{\rm nc}} - 1\right) = \frac{\sin^2\theta_\tau}{6}$$]

see de Gouvea for DUNE study



Oscillation pattern depends on amount of matter traversed

Super-K, arXiv:1410.2008

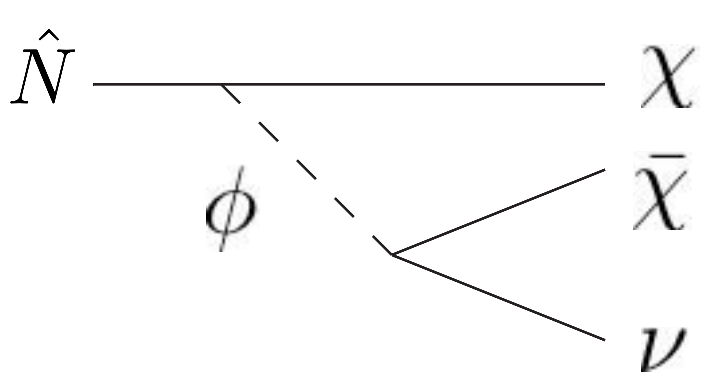
$\sin\theta_\tau < 0.42$ (stat. limited!)

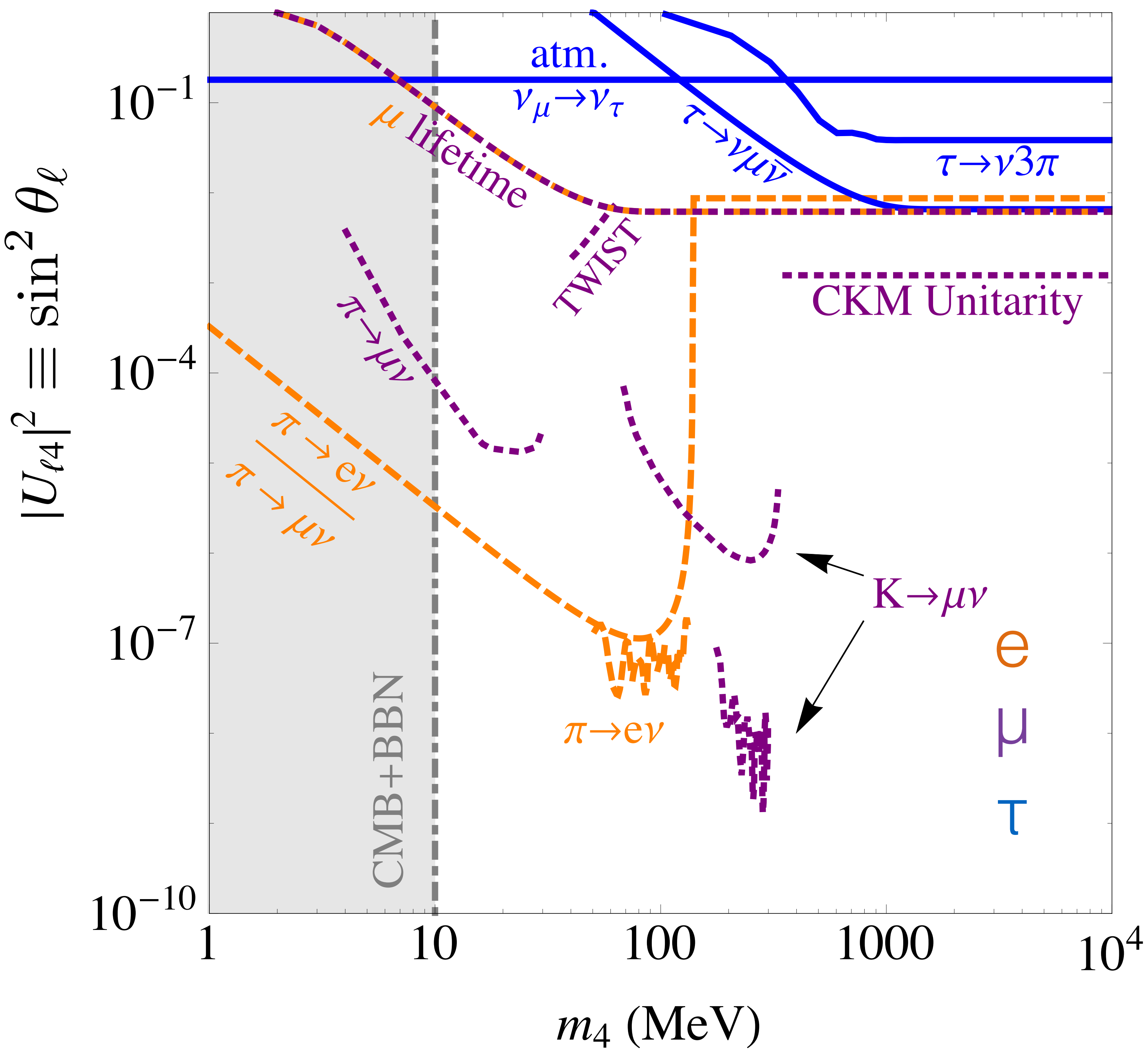
DM coupling to each neutrino flavor determined by mixing angle with sterile neutrino

Mixing angle affects known known neutrino properties

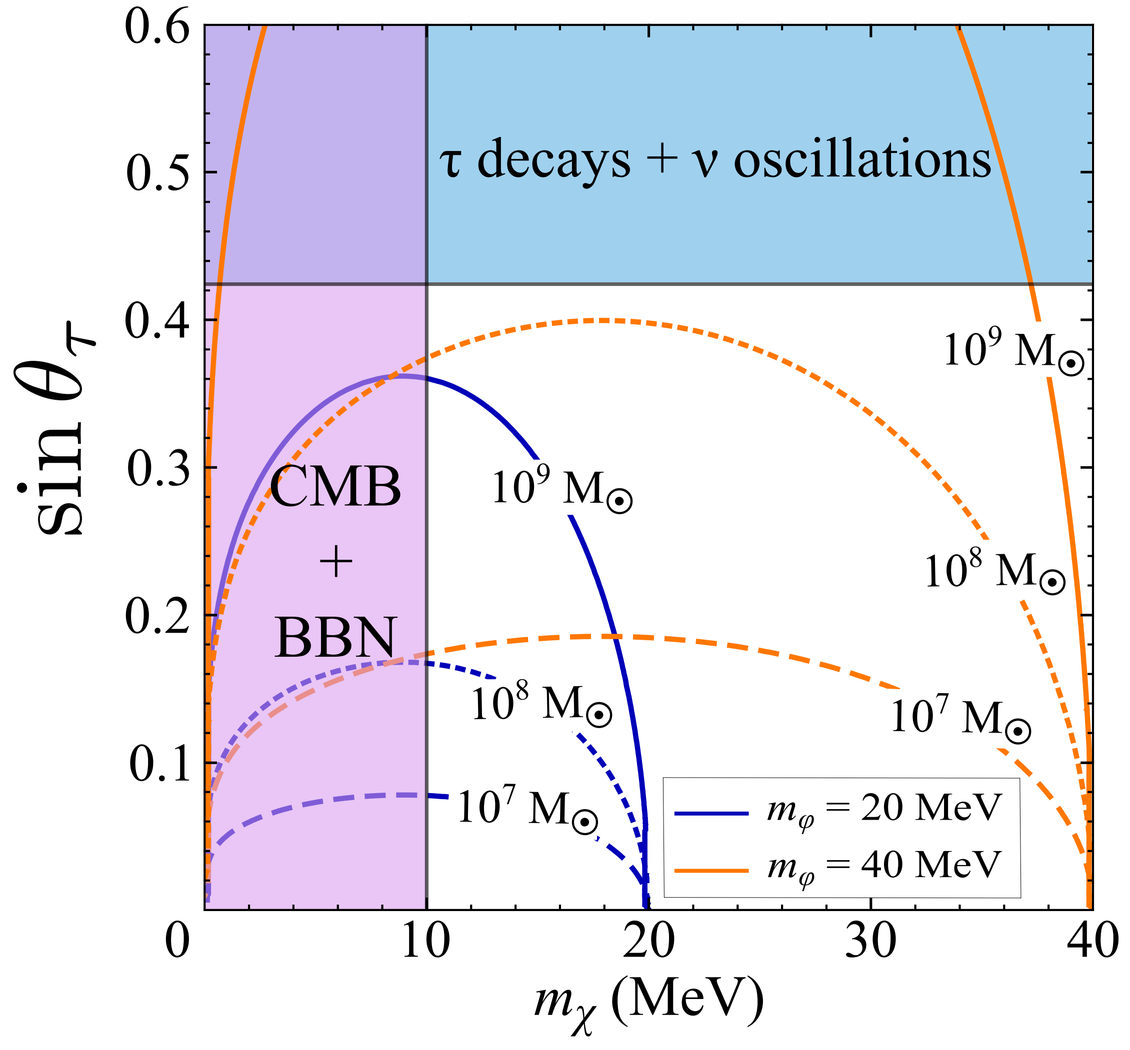
Strong limits on e, μ single out mixing with τ as promising

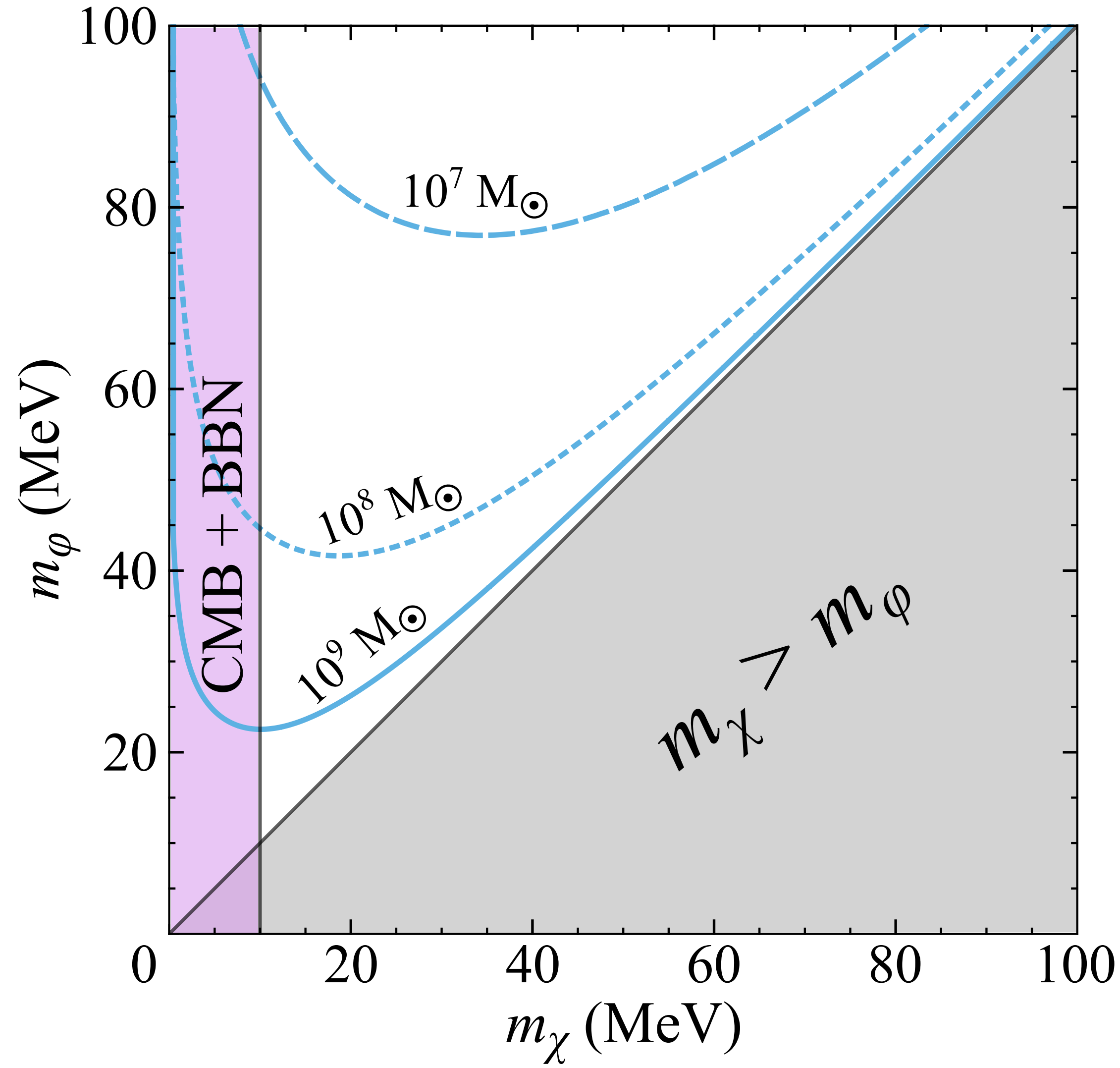
[Note: heavy (mostly sterile) ν decays invisibly]





Given these constraints, what M_{cut} can we achieve?



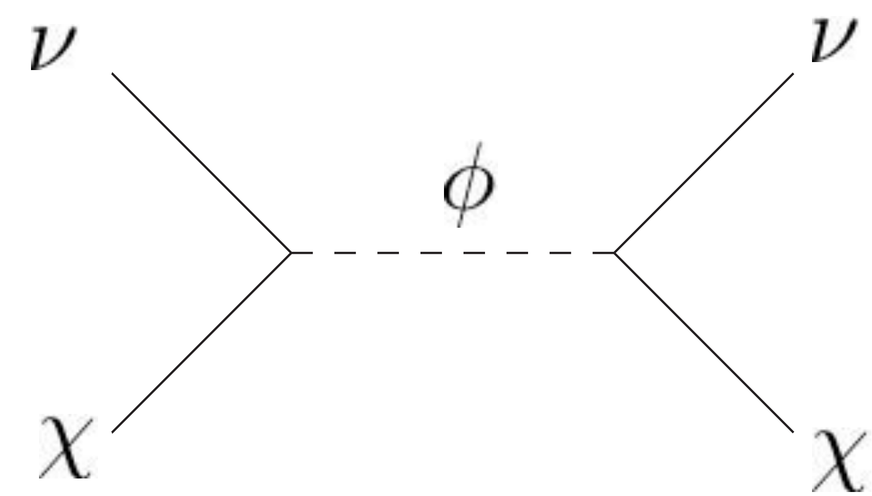


Find interesting values for 10-100 MeV masses

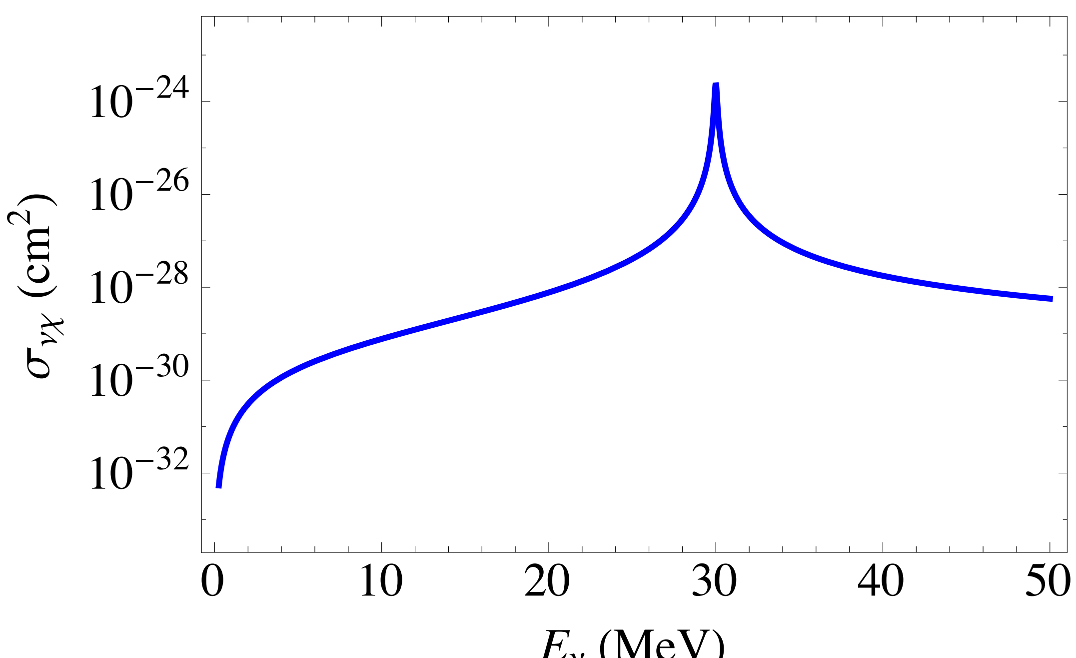
Other implications?

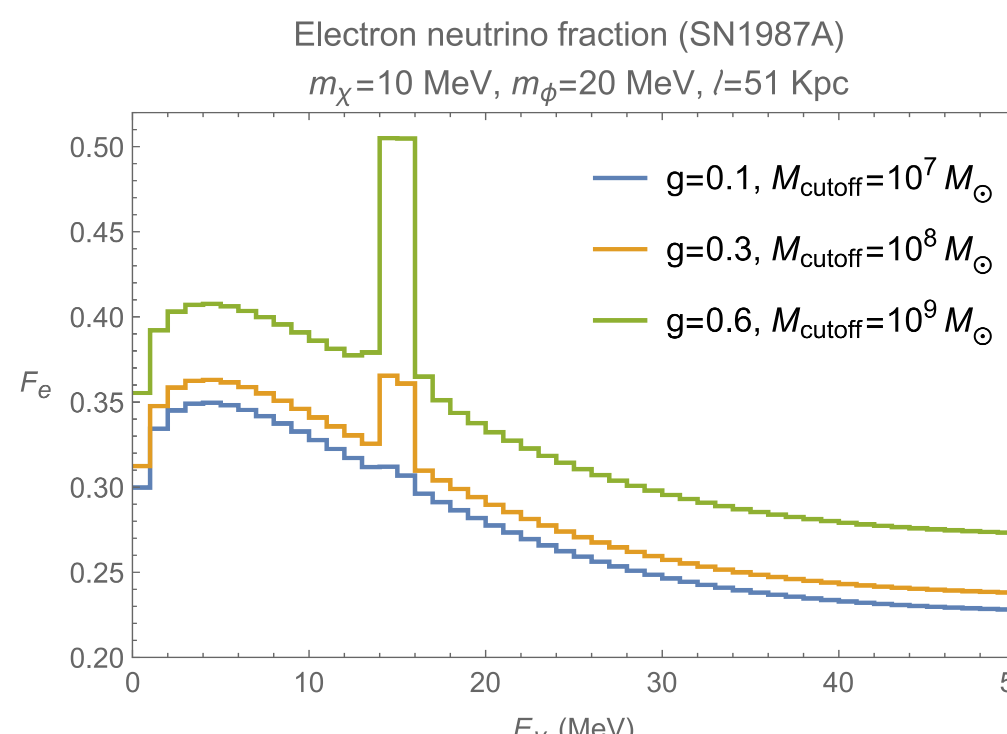
Neutrinos from Supernovae

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





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

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

(Further work in progress w/ Bertoni, Nelson & Reddy)

Supernovae Limits

Neutrinos produced in SN at T~30 MeV

Initial neutronization burst of ν_e followed by cooling

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

(Further work in progress w/ Bertoni, Nelson & Reddy)

Supernovae Limits

Large fraction of DM gravitationally bound: v_{esc} ~0.5 c

Is location (temperature) of ν-sphere changed?

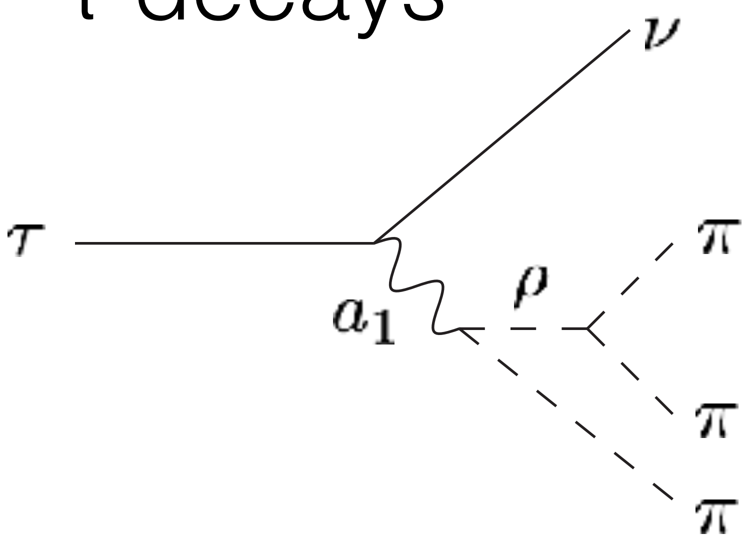
What are effects of flavor?

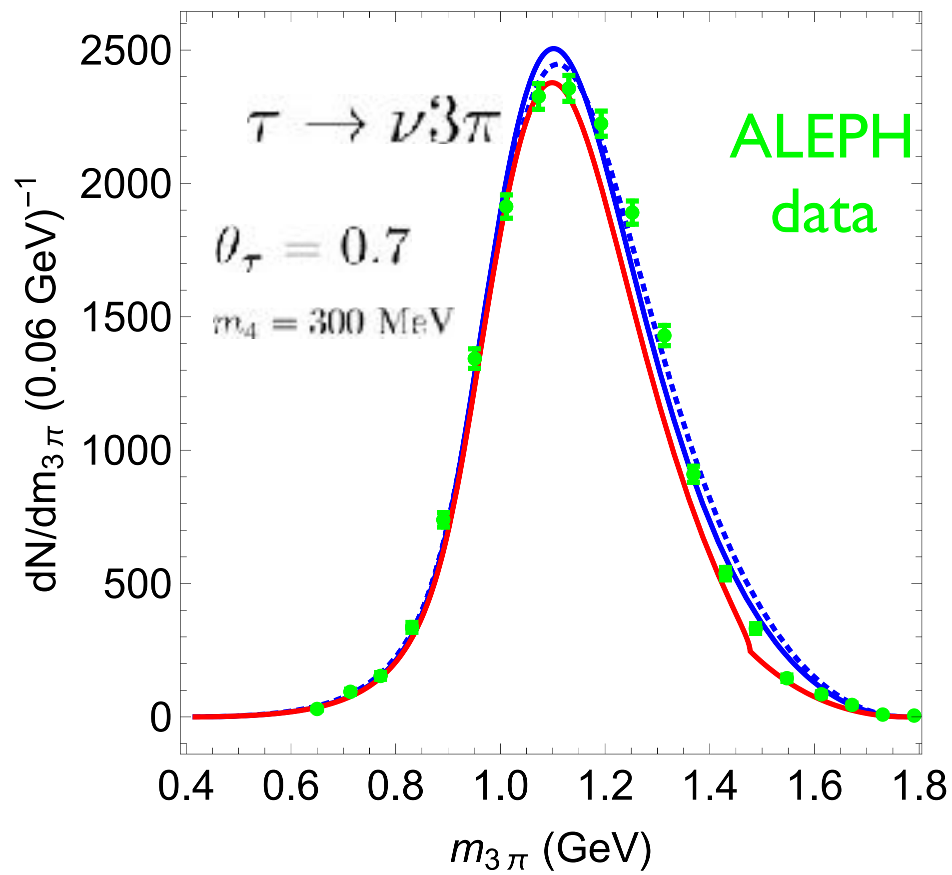
Could ν “dwell” time be increased?

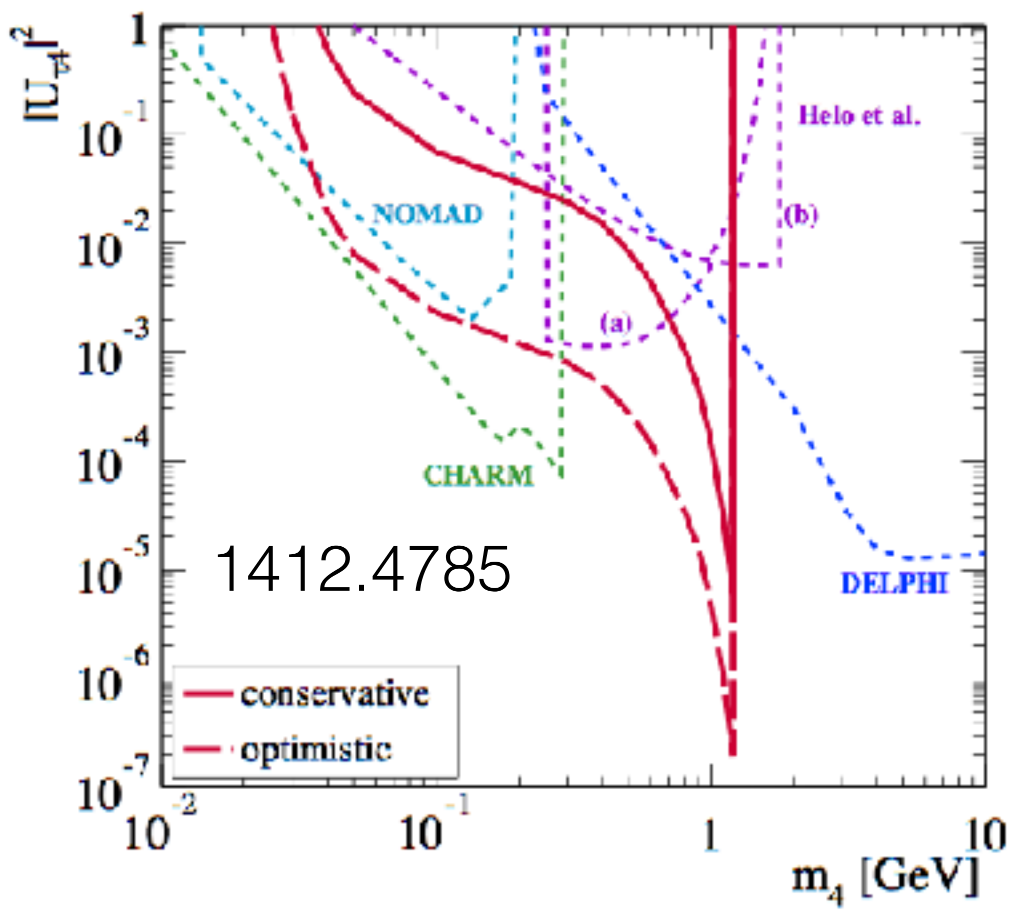
Very complicated…

Future tests

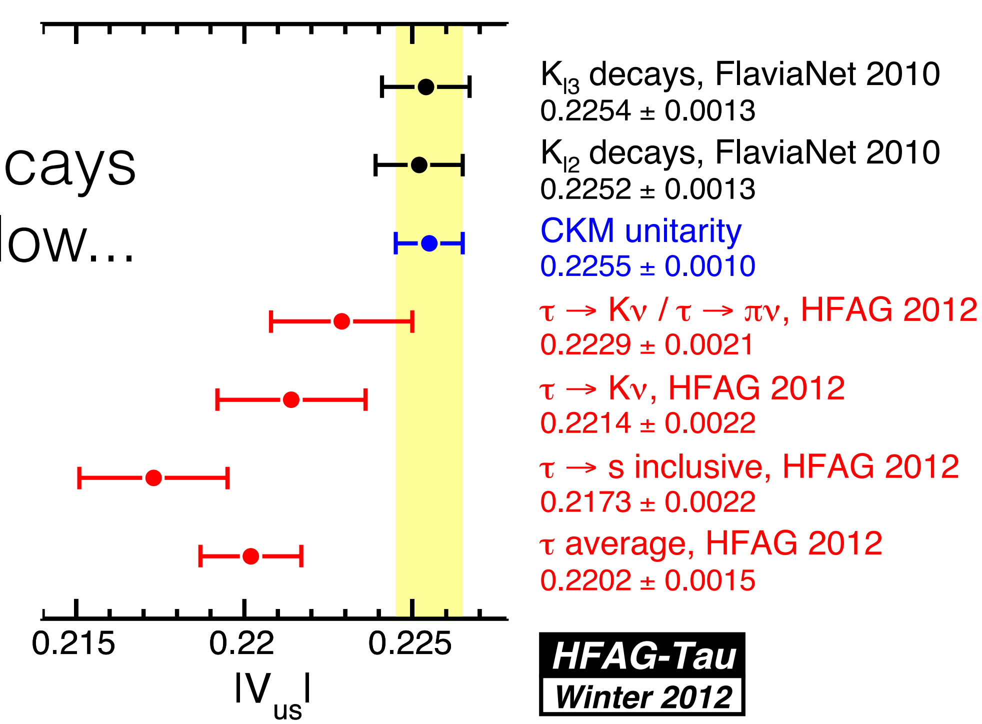
τ decays



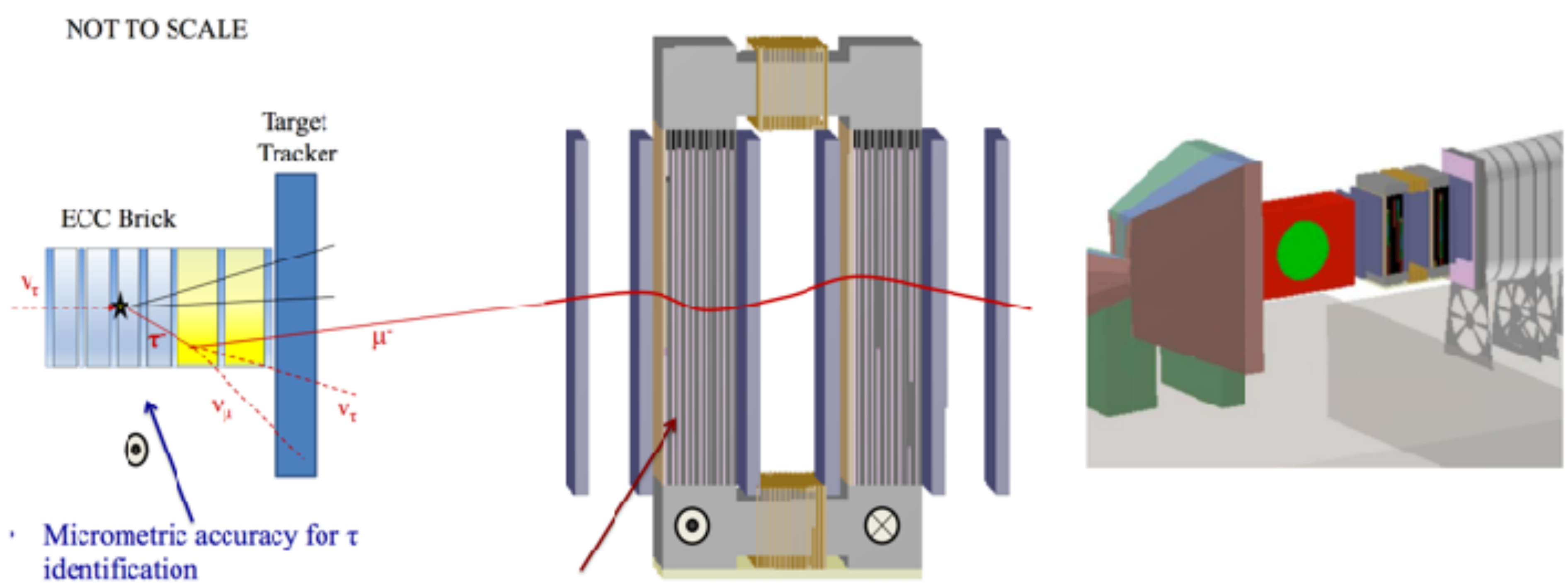




τ→K decays slightly low...



Question:
Can an $\mathcal{O}$(3-4k) ν_τ sample at SHiP impact a scenario like this?



(see talk by N. Serra)

Wrap up

Lots of observations point to DM

We know some general characteristics of DM

Structure formation tells us CDM paradigm might be under stress

Could be pointing to DM's nongrav. interactions!

Described (one way to get) DM-neutrino interactions

Can test it terrestrially!

Back up

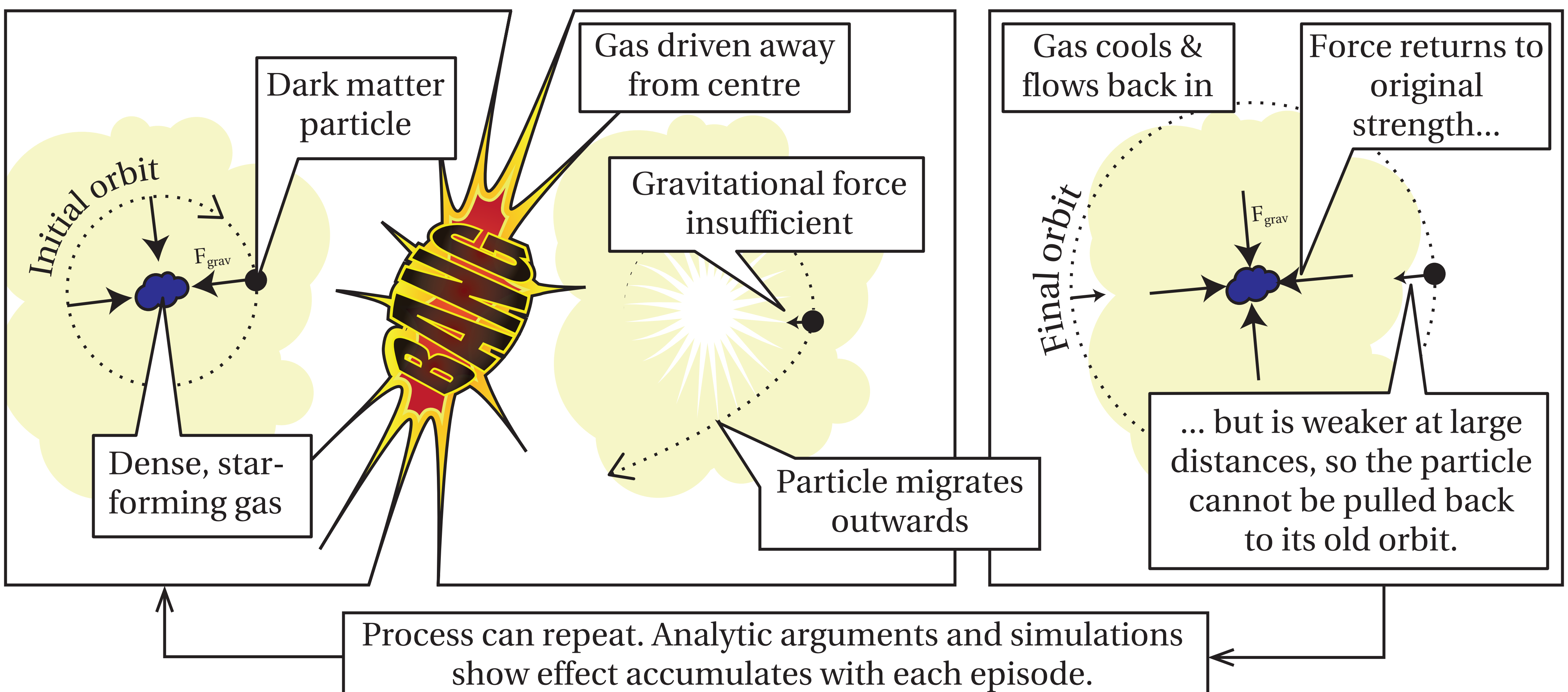
Neutrinos from SN: Core vs. Cusp?

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

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

transferred from SN to DM

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



Pontzen & Governato, 1402.1764

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

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

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

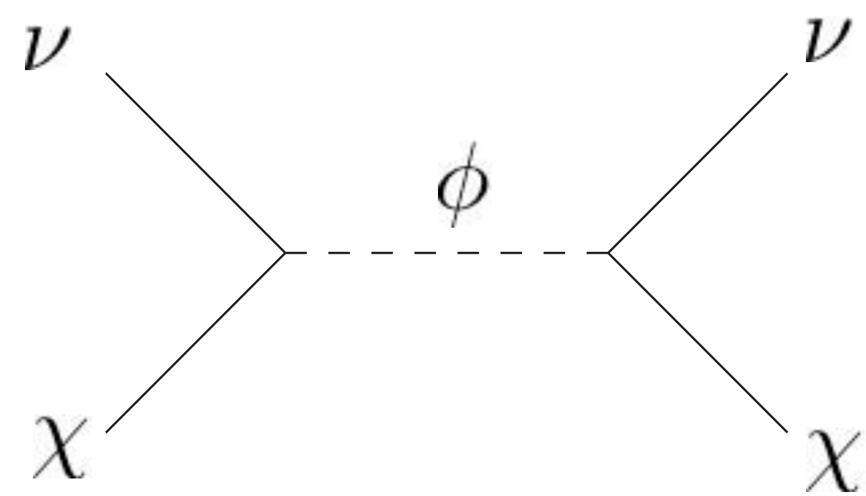
$$\Delta W \sim \frac{1}{30} \frac{G M_{\rm enc}^2}{r_0} \sim 3 \times 10^{54} \text{ ergs} \left(\frac{M_{\rm enc}}{10^9 M_\odot}\right)^2 \left(\frac{r_0}{\rm kpc}\right)$$

$$\Rightarrow N_{\rm SN} \times \epsilon_{\nu\chi} \sim 30$$

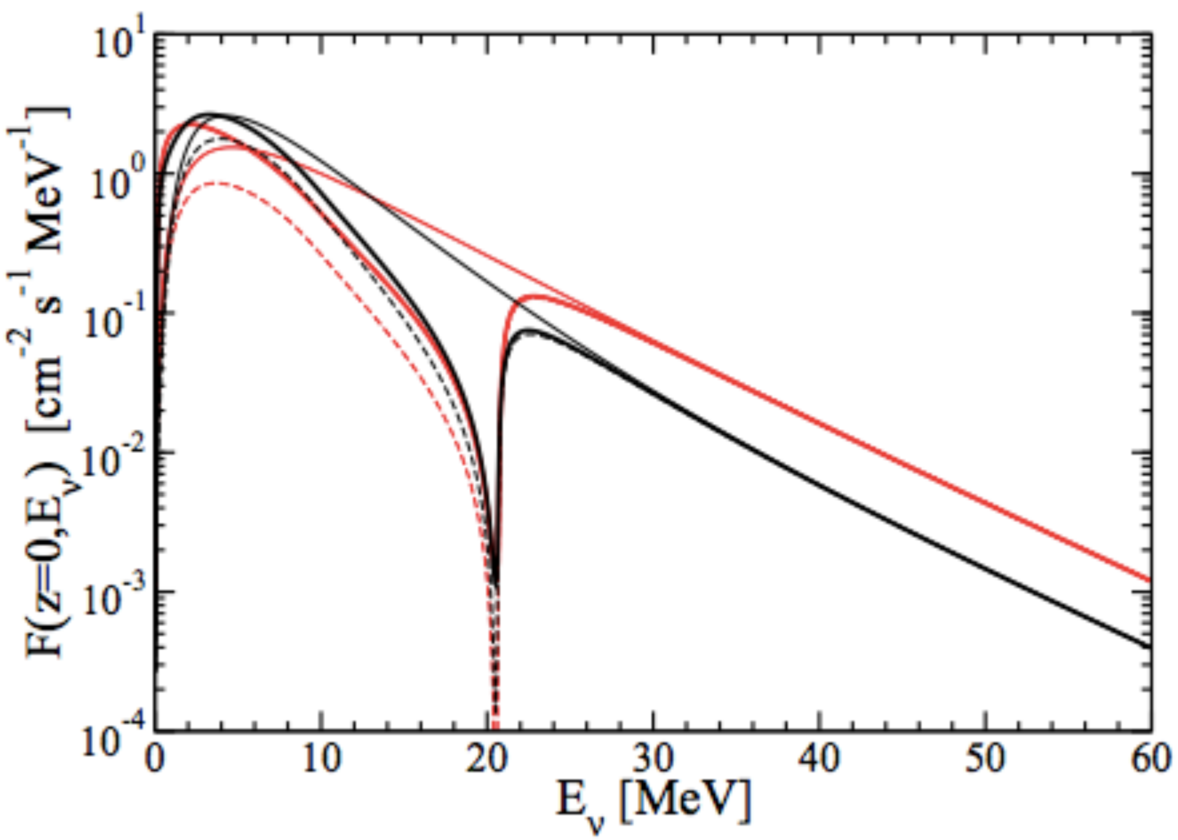
But only a small fraction of DM scattered...maybe including all stars? (In progress w/ Nelson & Weiner)

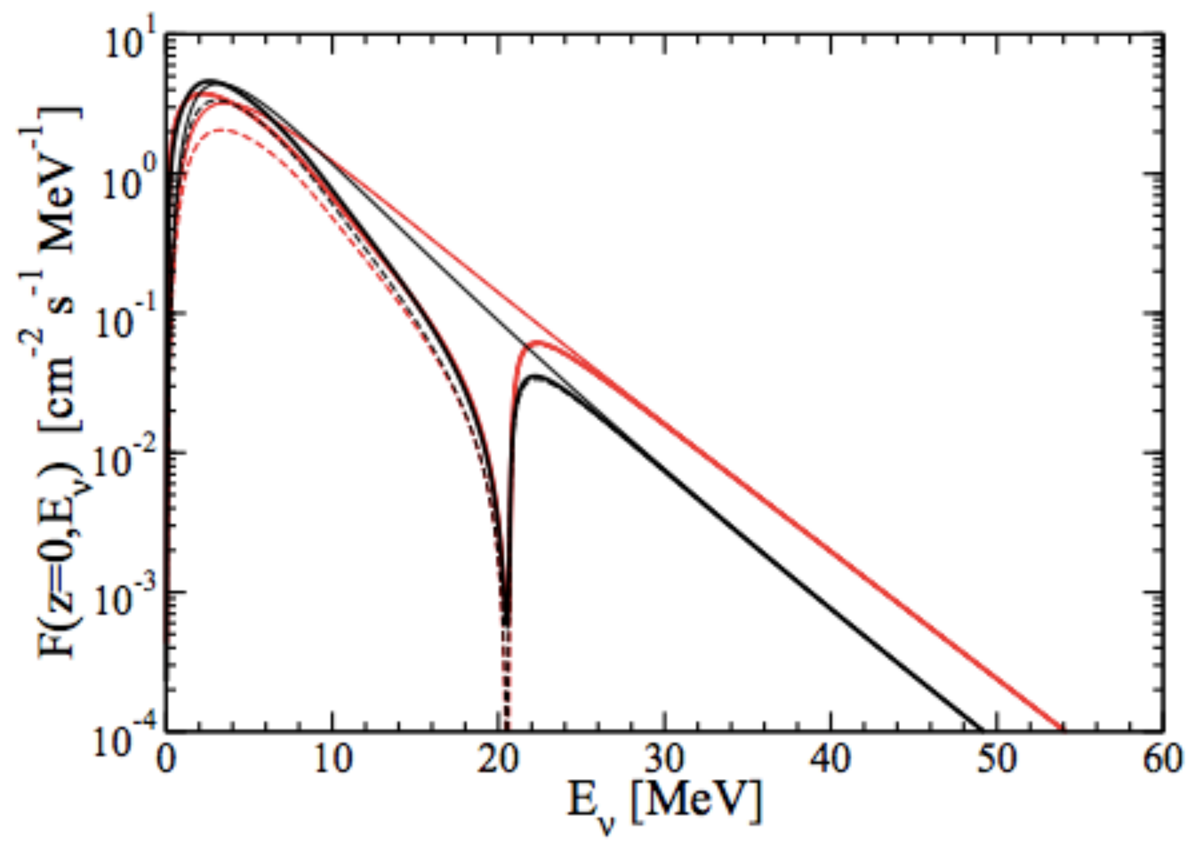
DSNB

Same process as for nearby SN



Farzan & Palomares-Ruiz 1401.7019



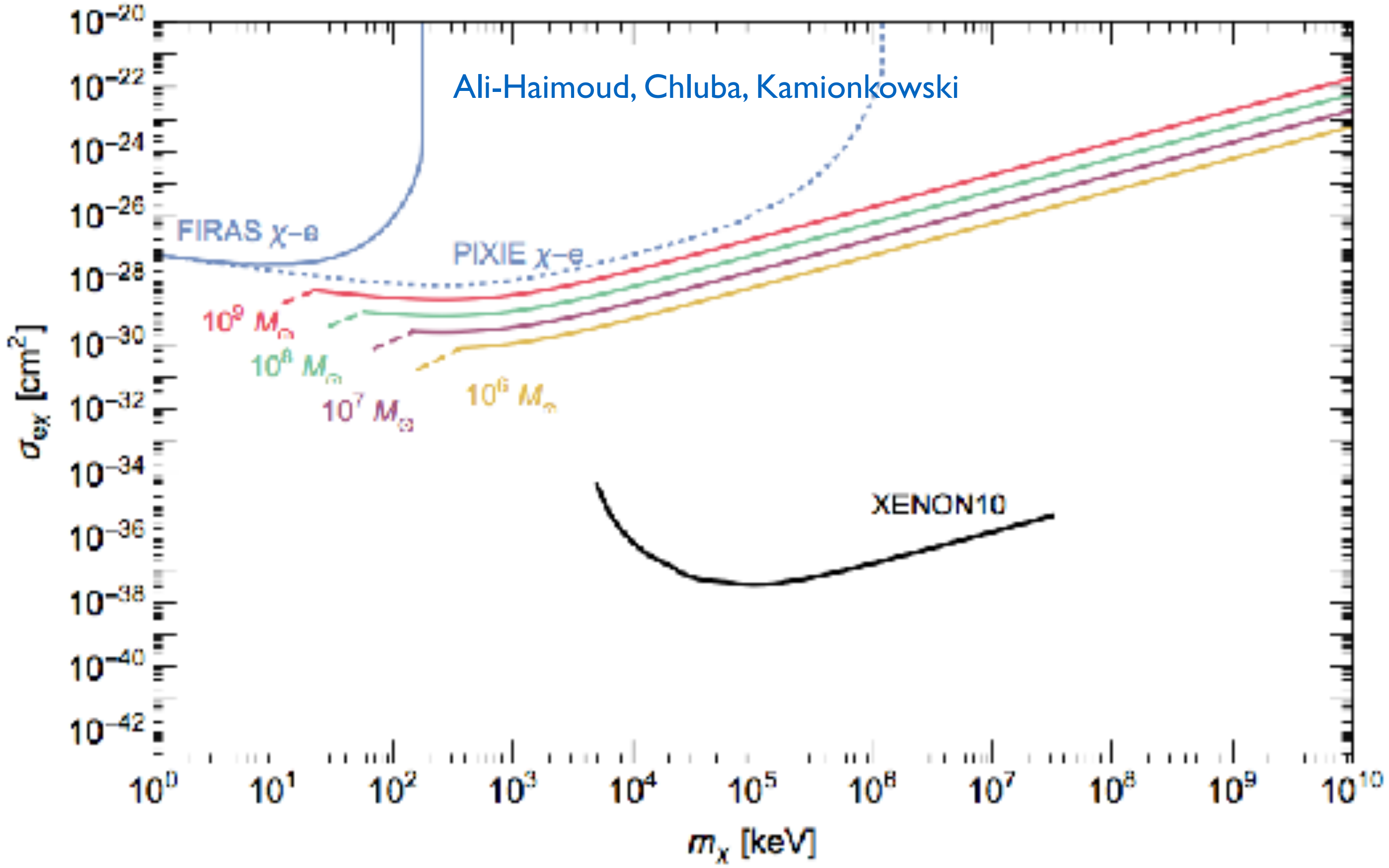


Potentially visible at Hyper-K

Couplings to electrons

What about couplings to other leptons?

Work in progress w/ R. Essig & Y. Zhong

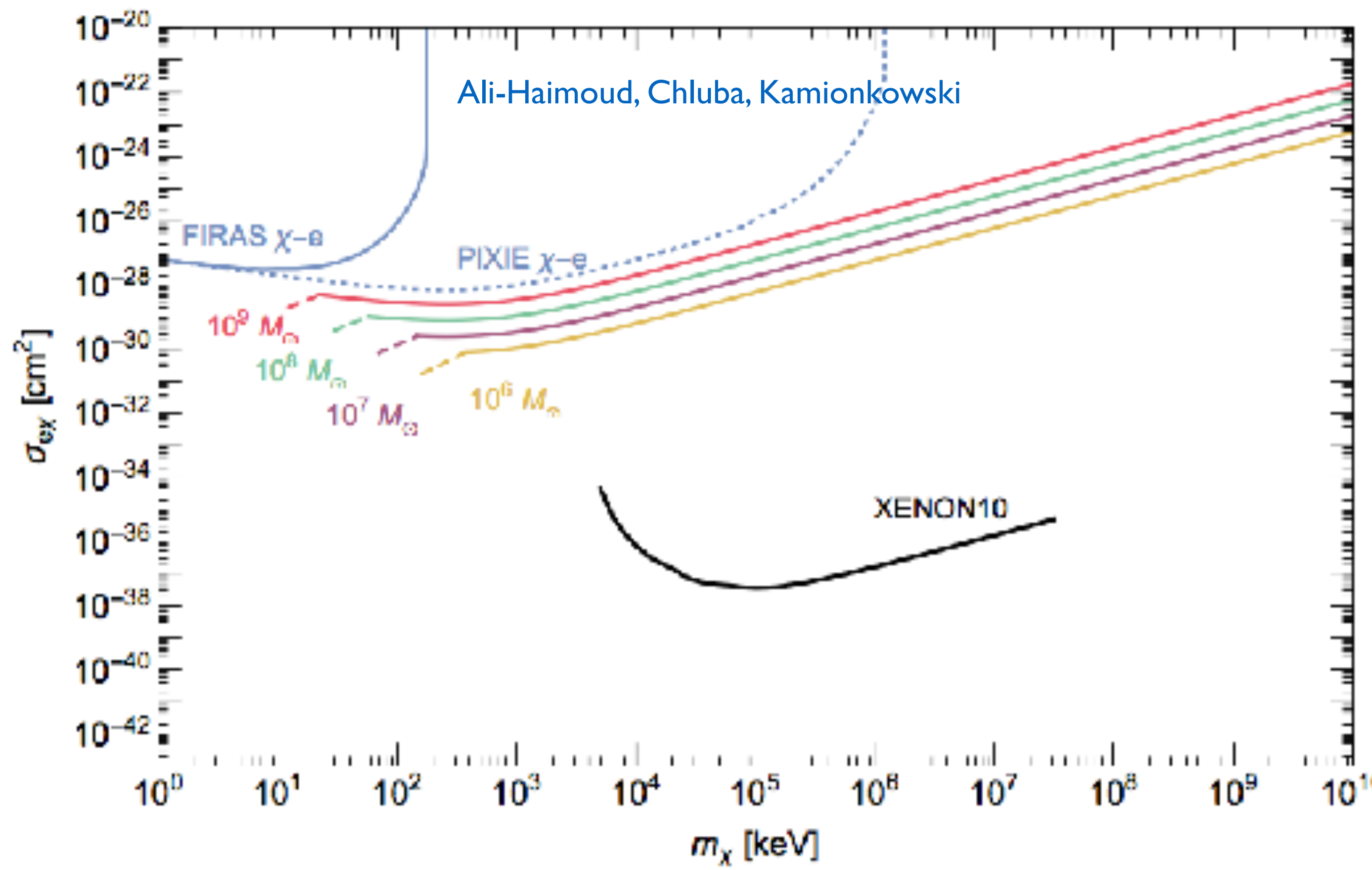


Couplings to electrons

$$\left(\frac{\rho_R}{\rho_\gamma}\right)_{\rm CMB} = 1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4_{\rm CMB} N_{\rm eff}$$
$$\equiv 1 + 0.2271\left(N^0_{\rm eff} + \Delta N_{\rm eff}\right)$$

Annihilation to electrons/photons gives negative contribution to $\Delta N_{\rm eff}$ canceled by, e.g., sterile neutrino

Work in progress w/ R. Essig & Y. Zhong



Couplings to electrons

$$\left(\frac{\rho_R}{\rho_\gamma}\right)_{\rm CMB} = 1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4_{\rm CMB} N_{\rm eff}$$

$$\equiv 1 + 0.2271\left(N^0_{\rm eff} + \Delta N_{\rm eff}\right)$$

Annihilation to electrons/photons gives negative contribution to $\Delta N_{\rm eff}$ canceled by, e.g., sterile neutrino

BBN constraints on $\Delta N_{\rm eff}$ weakened if there is a $\nu - \bar{\nu}$ asymmetry