Sterile Neutrino Portals

David McKeen
University of Pittsburgh
ACFI Neutrino Workshop
July 19, 2017

Sterile Neutrino Portals [and Dark Matter(s)]

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Model Building a Dark Sector
or: what is a "portal"?

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

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

$$H = \begin{pmatrix} \rho^+ \\ v + h + \rho^0 \end{pmatrix} \qquad G_\mu^a,\ W_\mu^b,\ B_\mu \to G_\mu^a,\ A_\mu$$

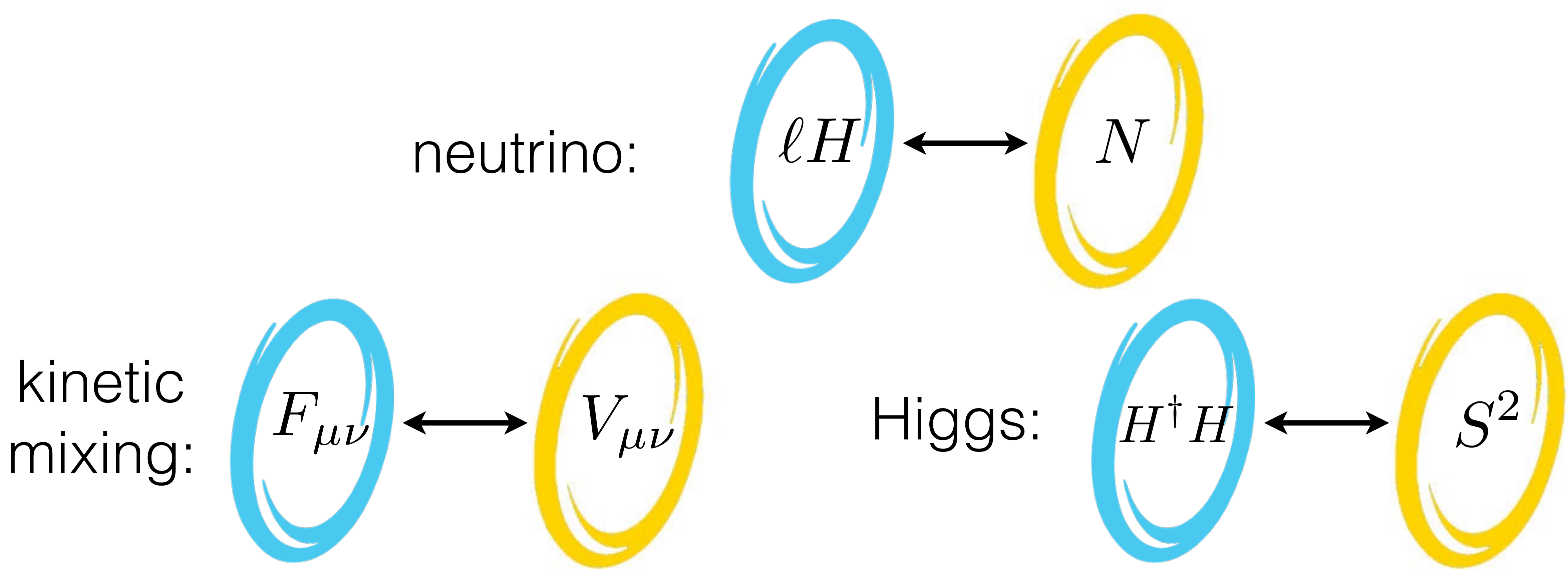
Renormalization: lower dim. operators (fewer fields/particles) more important

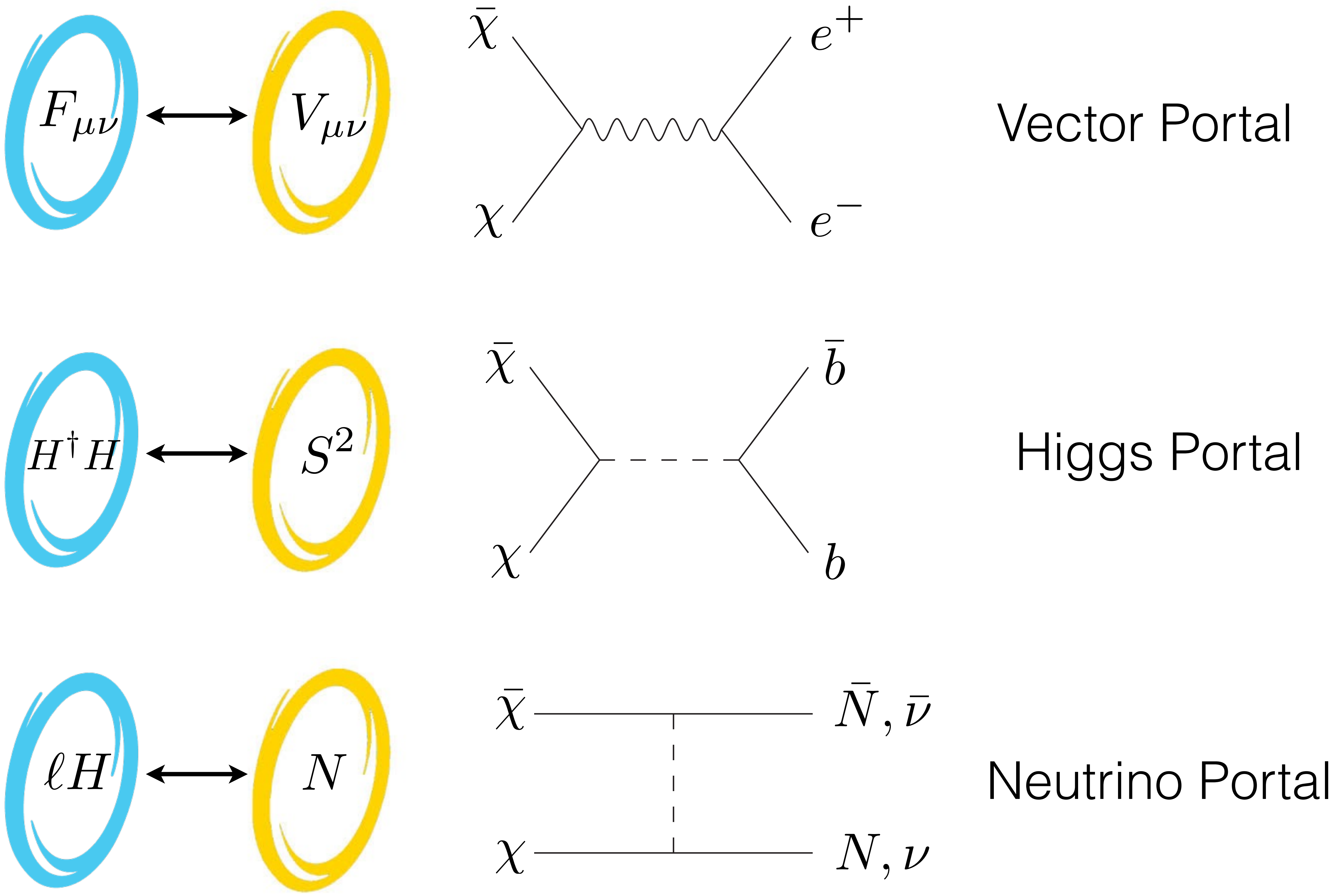
Model Building a Dark Sector
or: what is a “portal”?

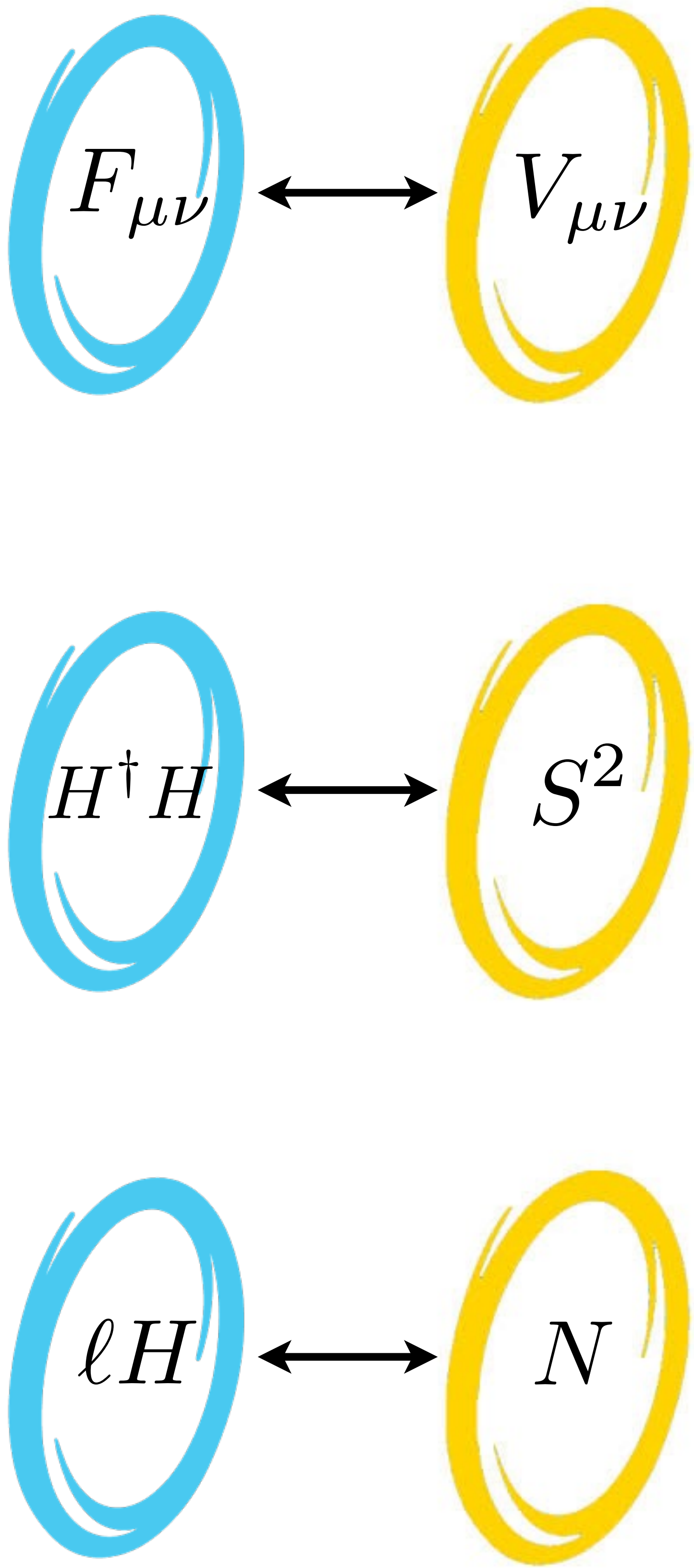
Standard Model symmetries $SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_{\rm em}$

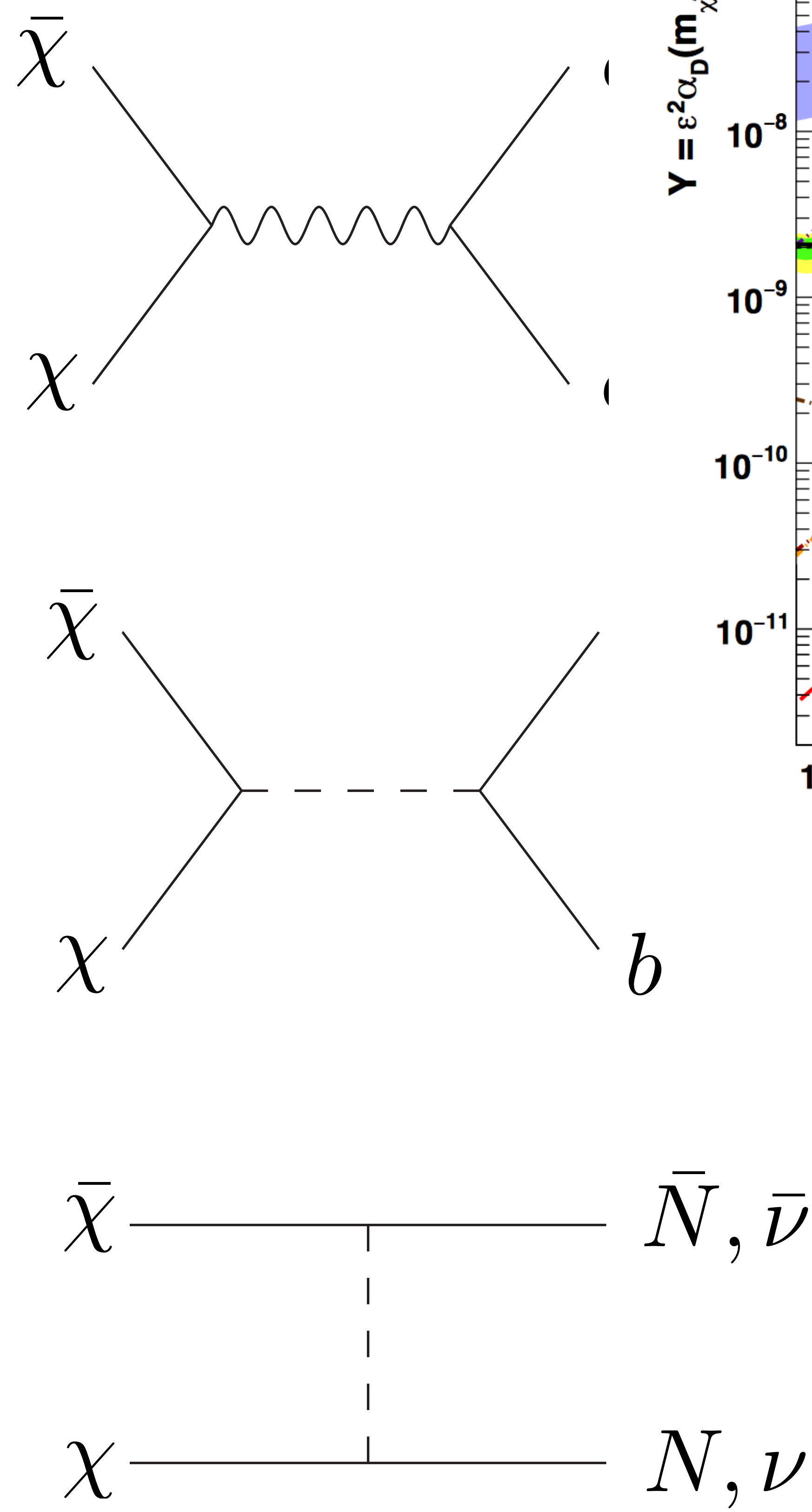
Portals: coupling via stuff uncharged w.r.t. SM

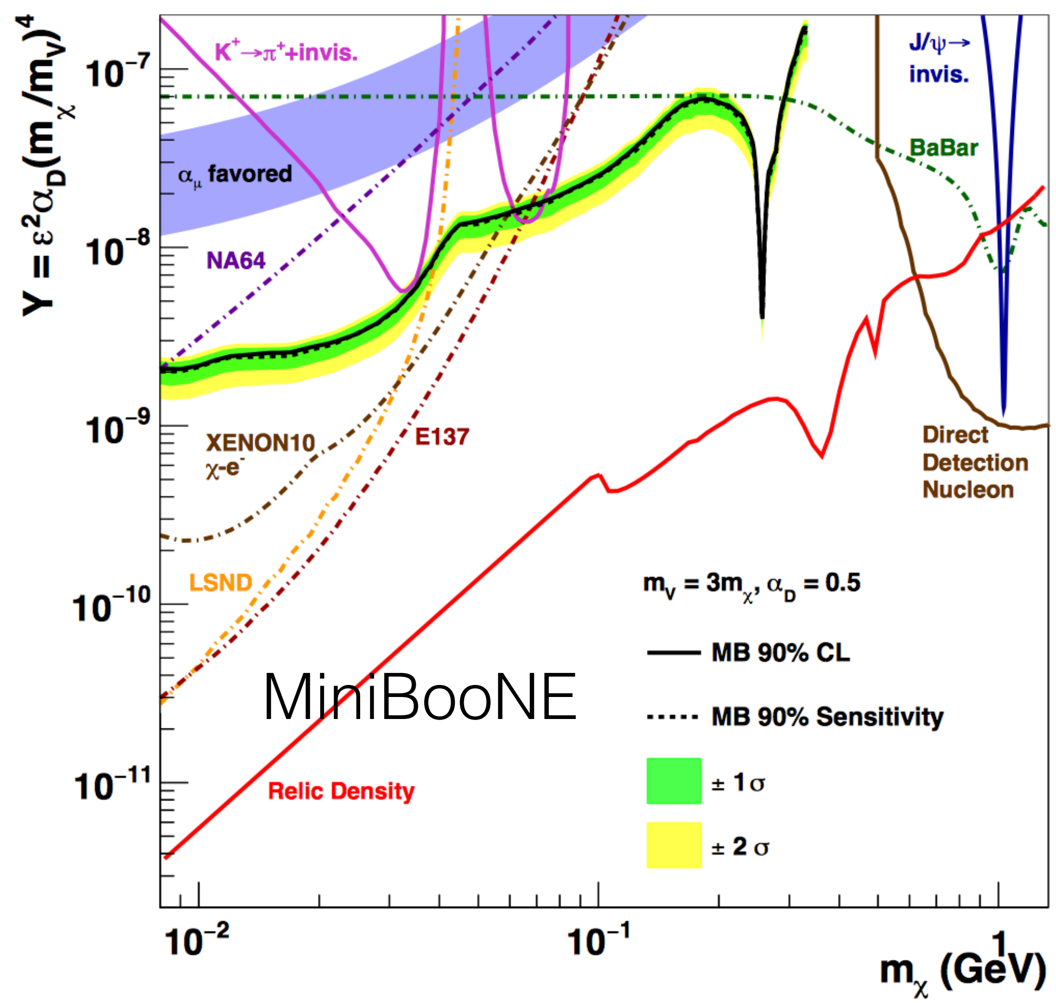
Lead to minimal difficulties incorporating hidden sectors



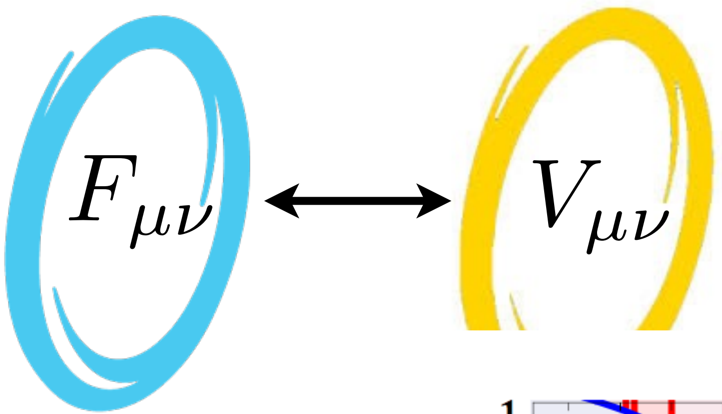

$F_{\mu\nu}$
$V_{\mu\nu}$
$\bar{\chi}$
χ
e^+
e^-
Vector Portal
$H^\dagger H$
S^2
$\bar{\chi}$
χ
$\bar{b}$
b
Higgs Portal
ℓH
N
$\bar{\chi}$
χ
$\bar{N}, \bar{\nu}$
N, ν
Neutrino Portal

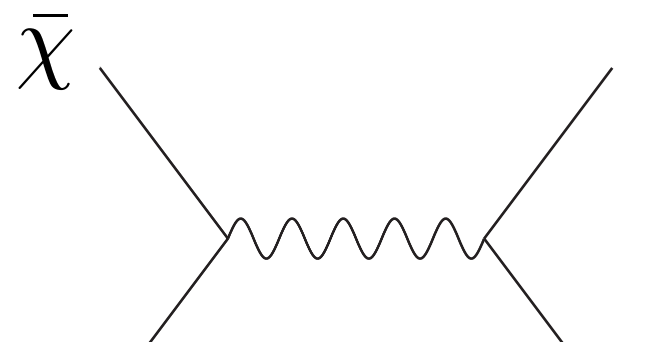


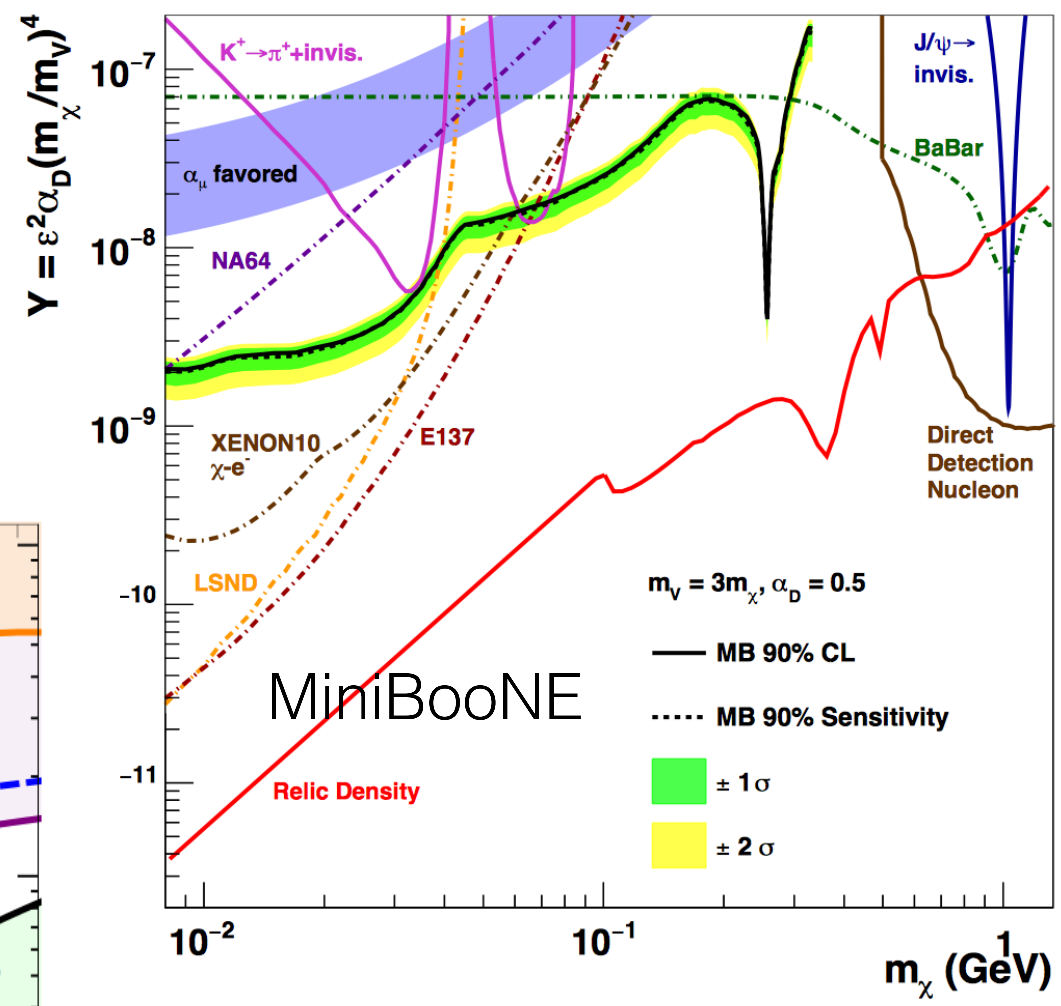


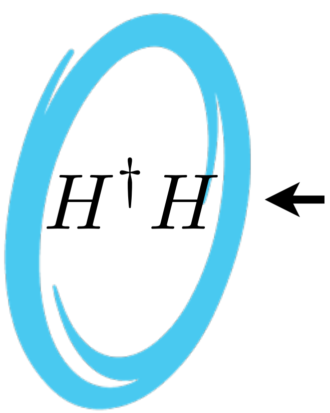


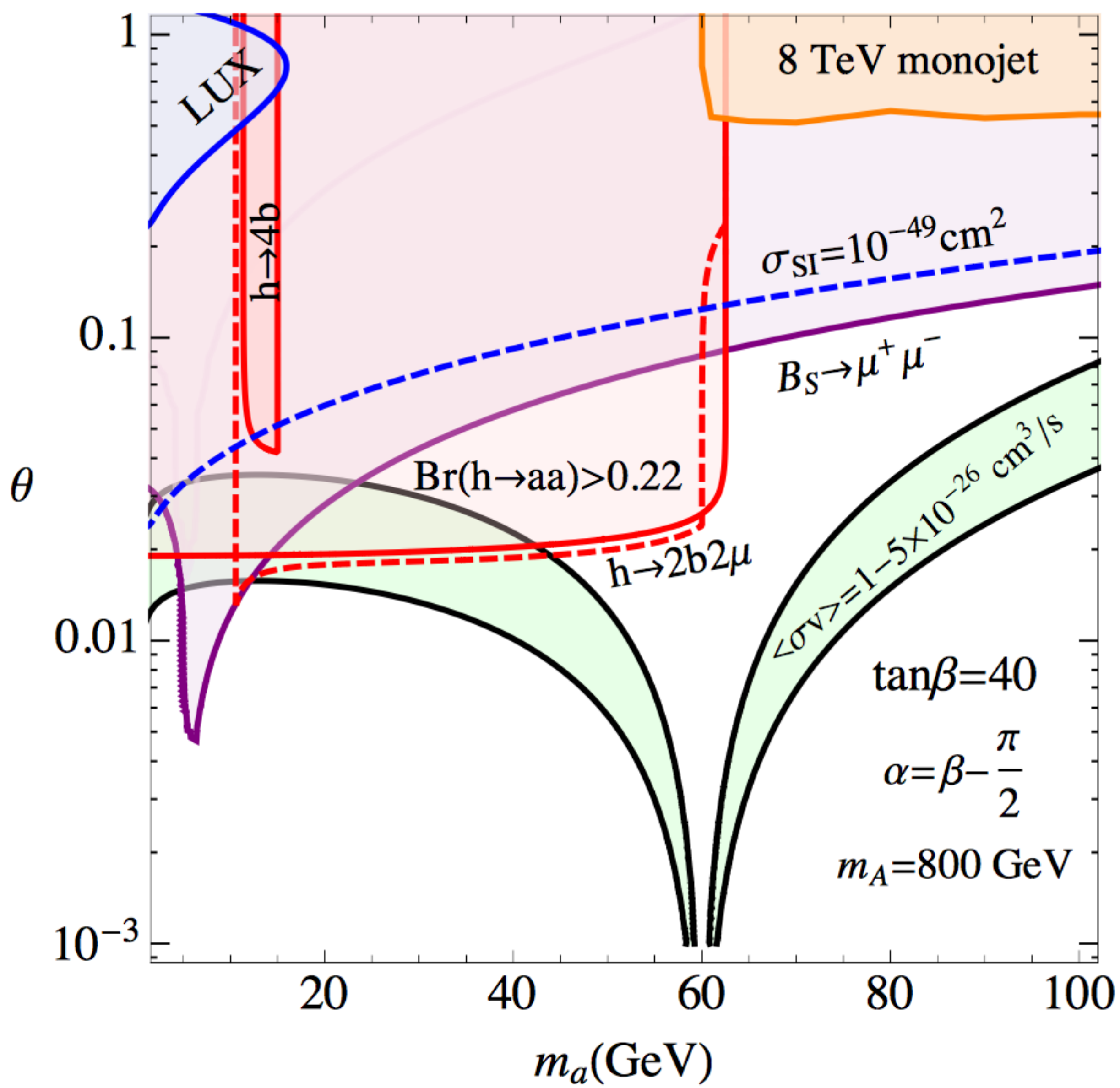
Neutrino Portal

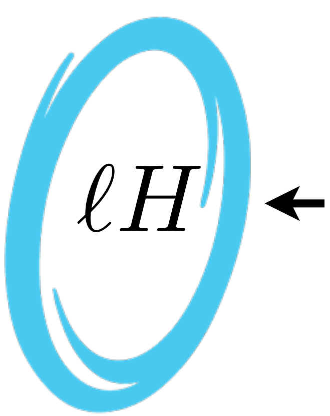








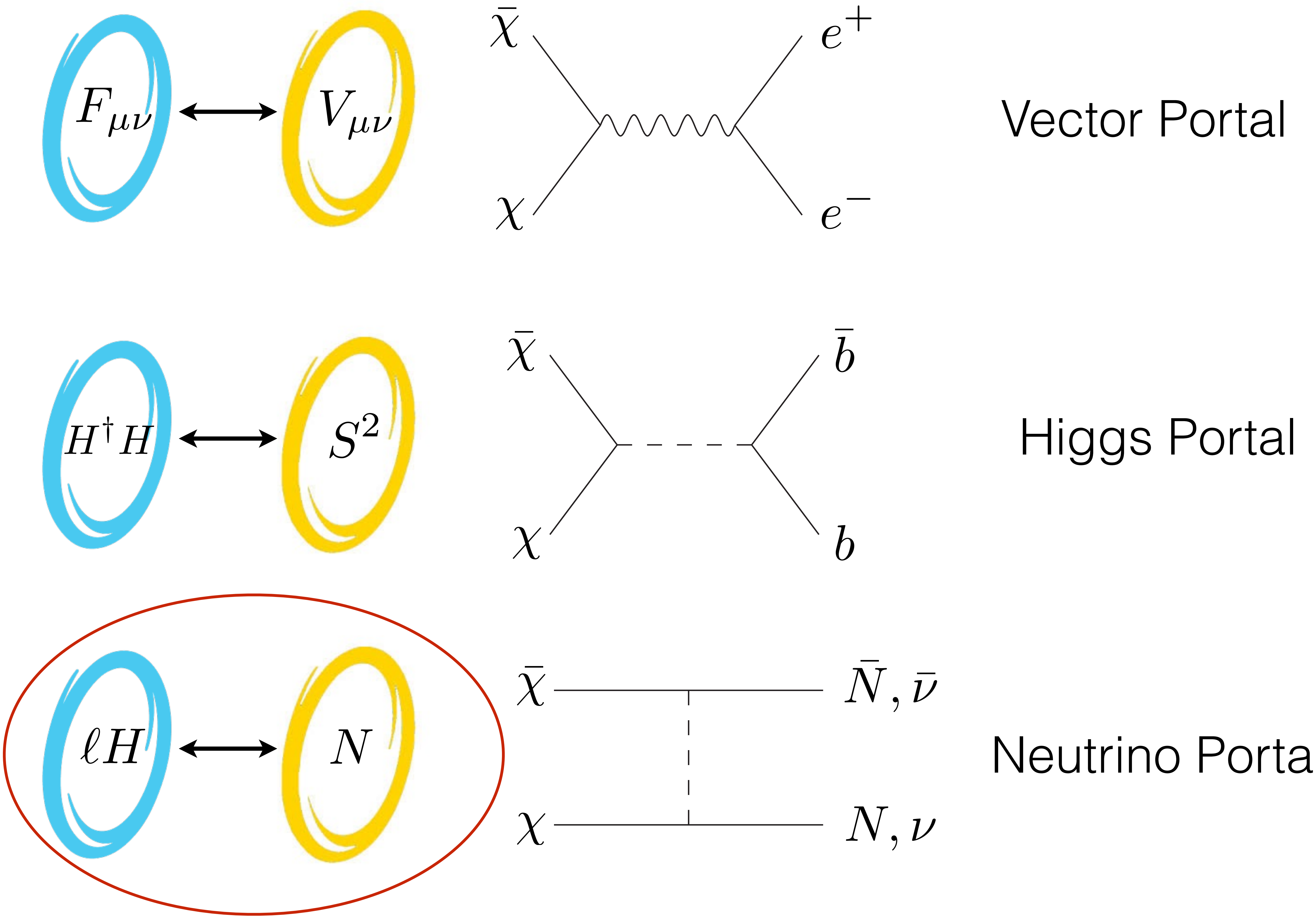




$\bar{\nu}$

Neutrino Portal

ν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Vector Portal
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S^2
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Higgs Portal
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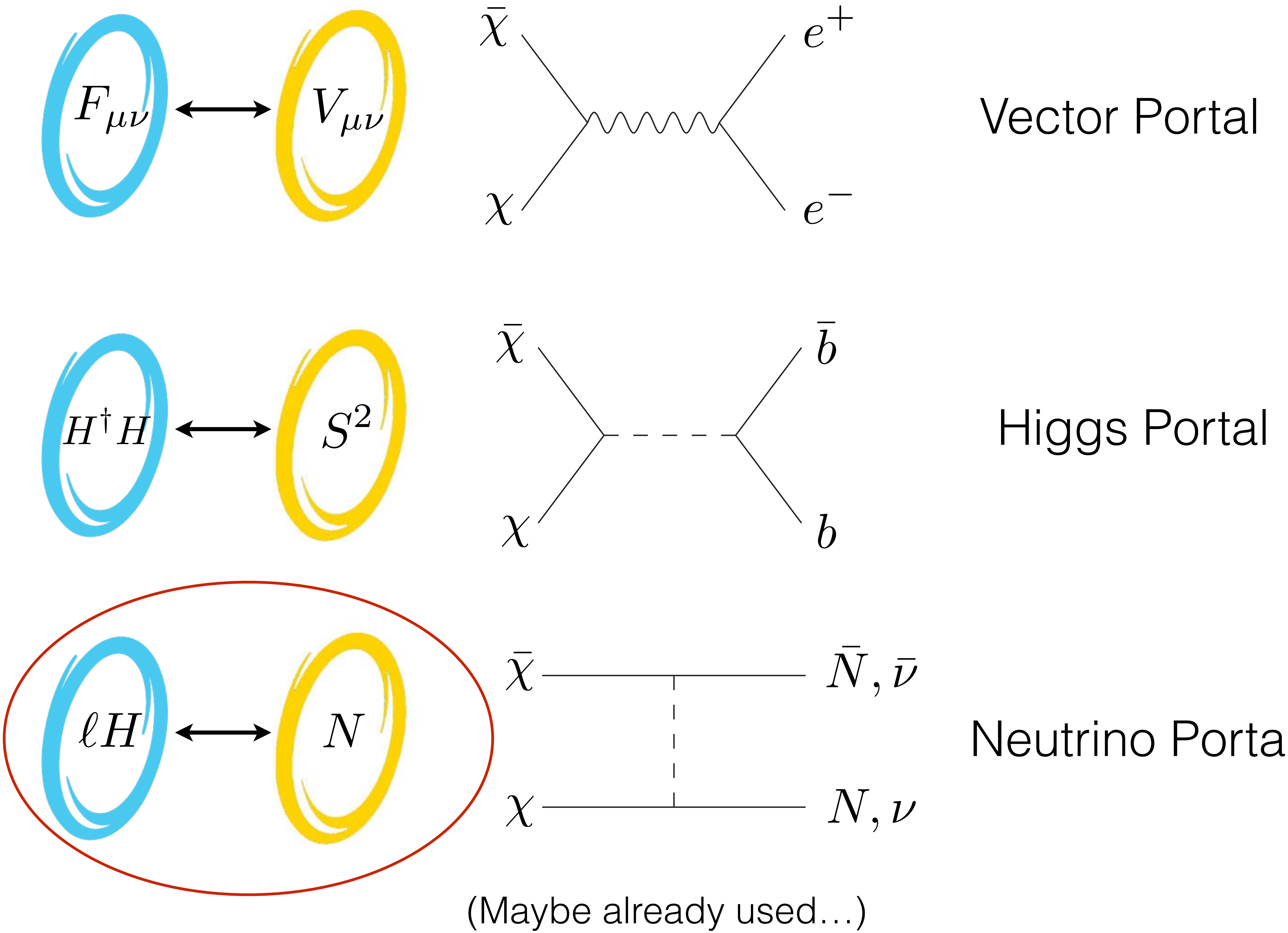
$\bar{\chi}$
χ
$\bar{N}, \bar{\nu}$
N, ν
Neutrino Portal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$V_{\mu\nu}$
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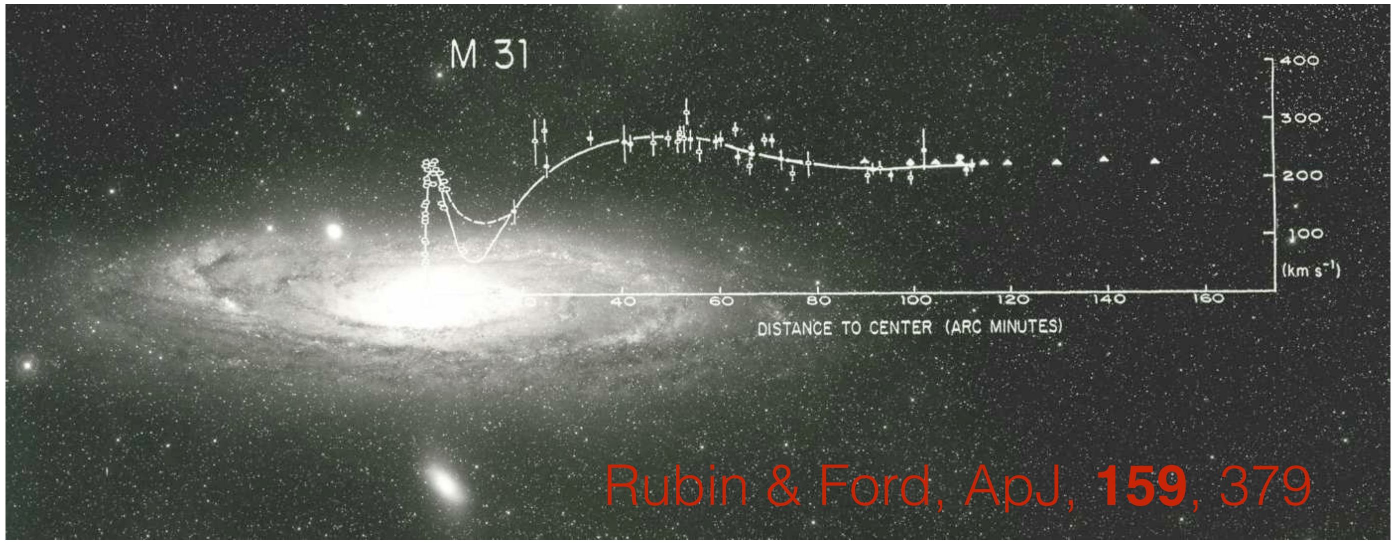
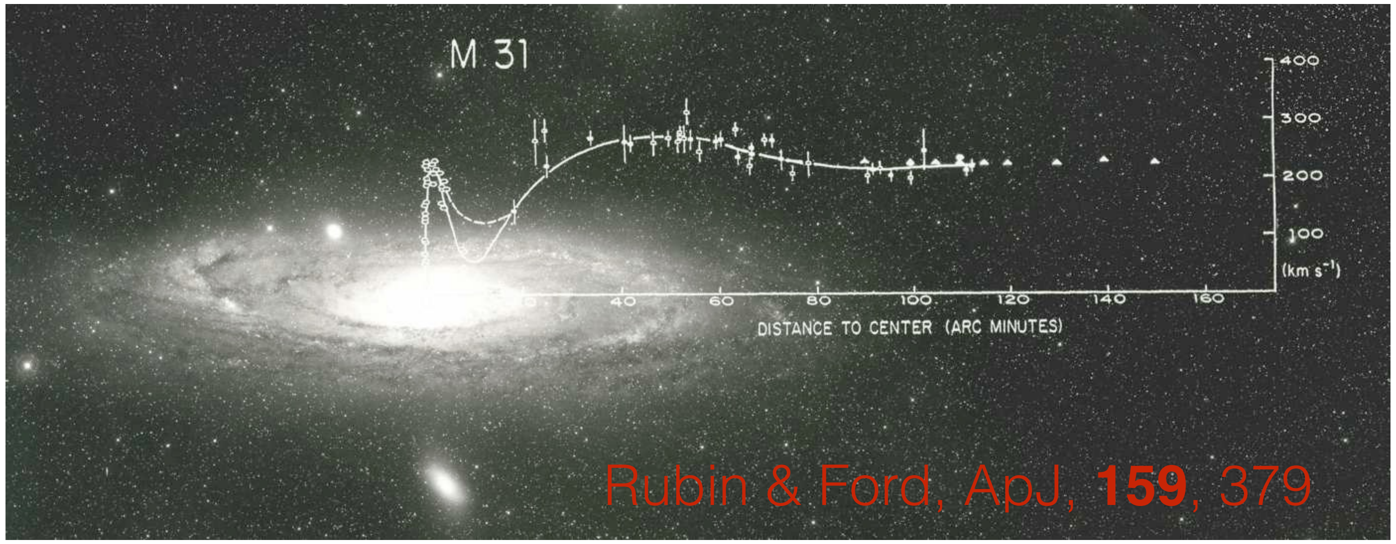
e^+
e^-
Vector Portal
$H^\dagger H$
S^2
$\bar{\chi}$
χ
$\bar{b}$
b
Higgs Portal
ℓH
N
$\bar{\chi}$
χ
$\bar{N}, \bar{\nu}$
N, ν
Neutrino Portal
(Maybe already used…)

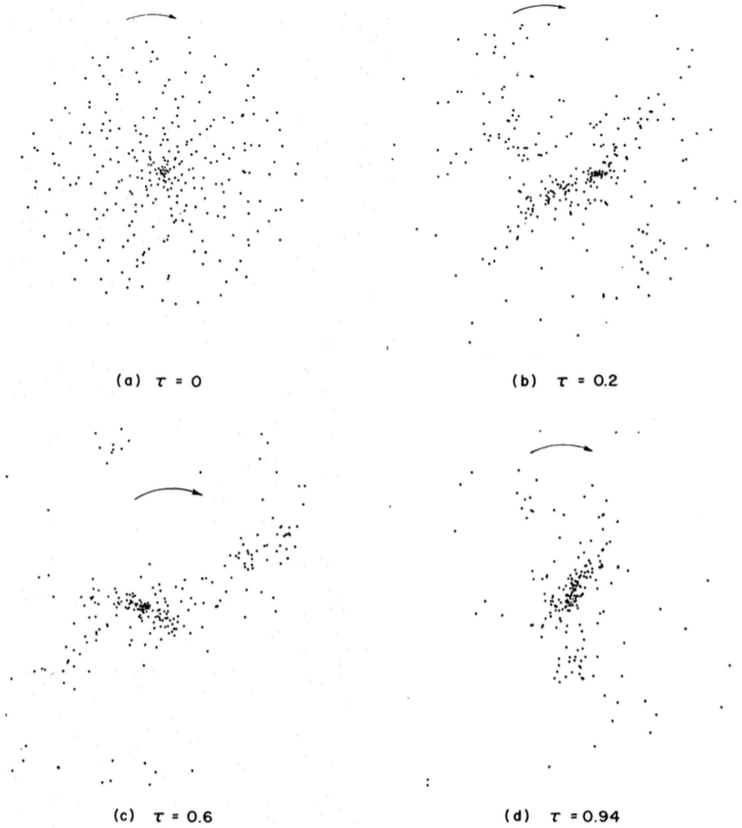
Why bother with a portal?



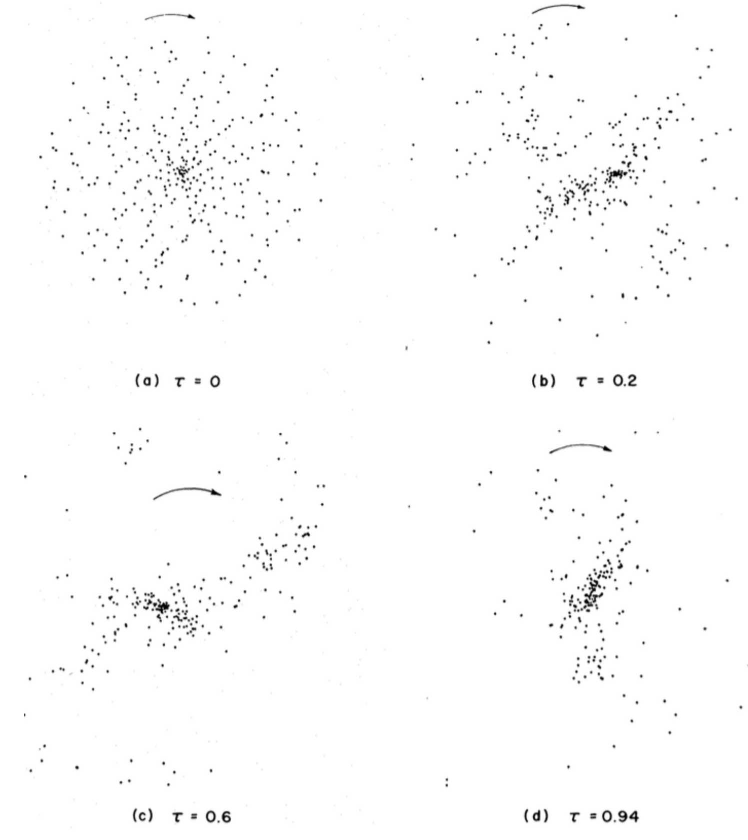
Rubin & Ford, ApJ, **159**, 379

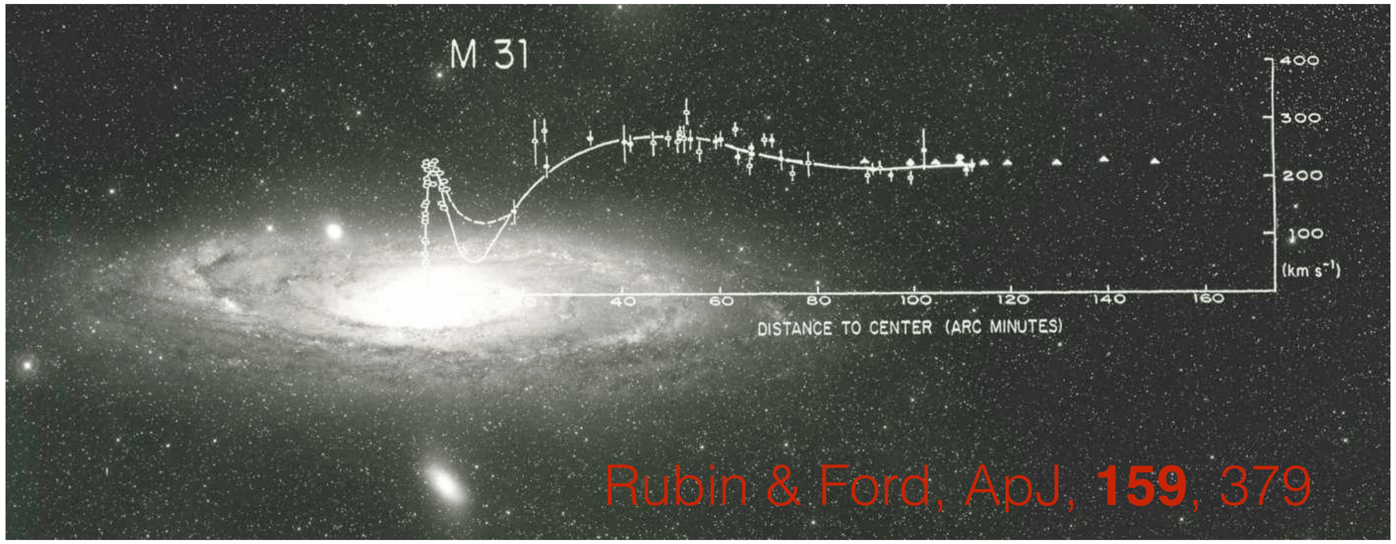
Ostriker & Peebles, ApJ, **186**, 467 ('73)

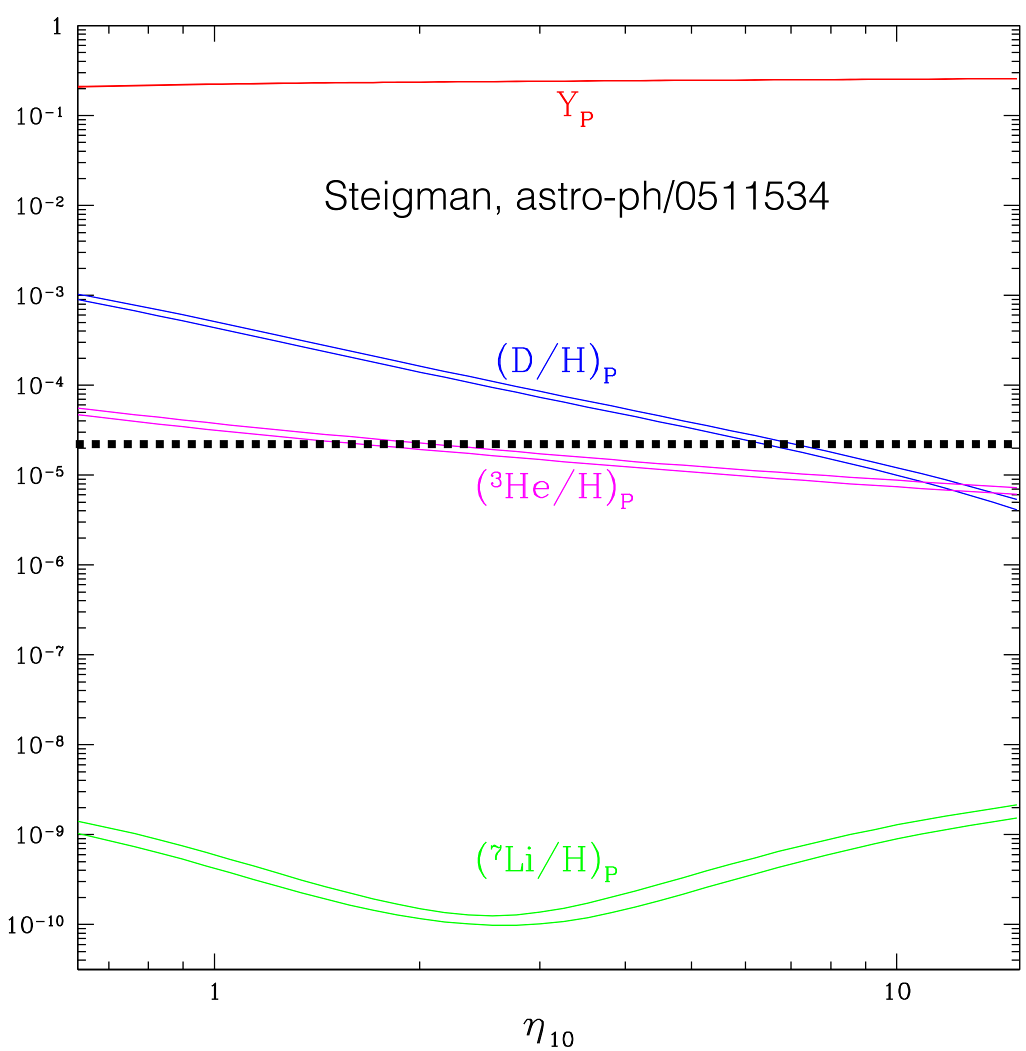


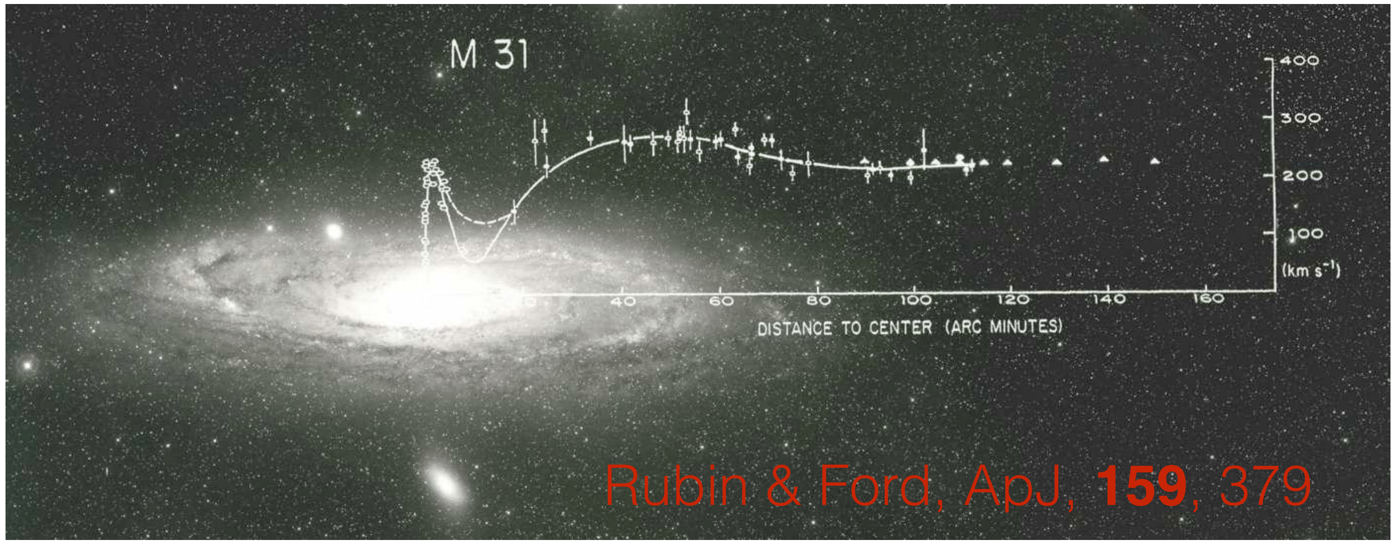


Ostriker & Peebles, ApJ, **186**, 467 ('73)









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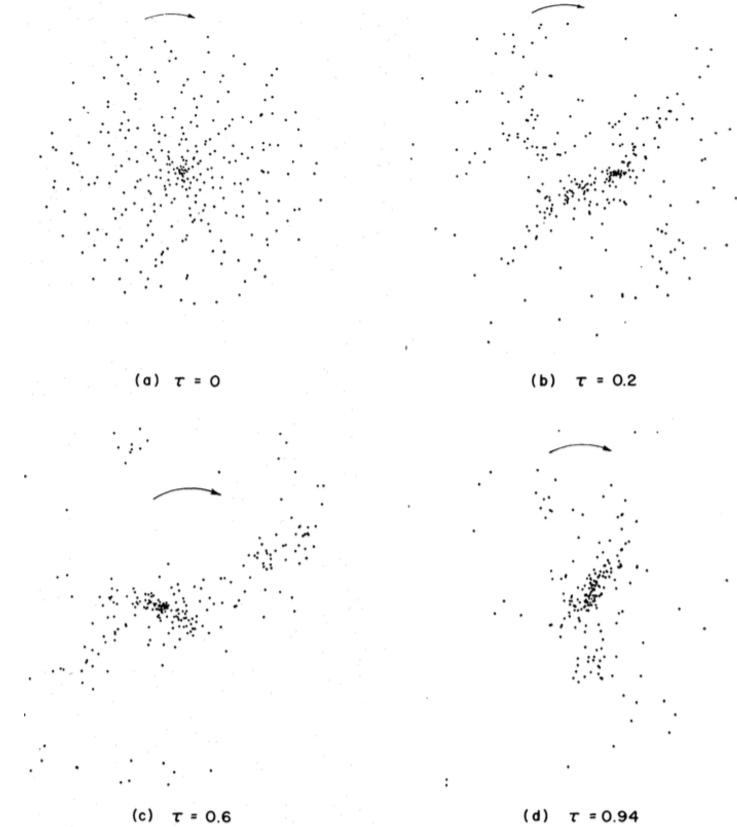

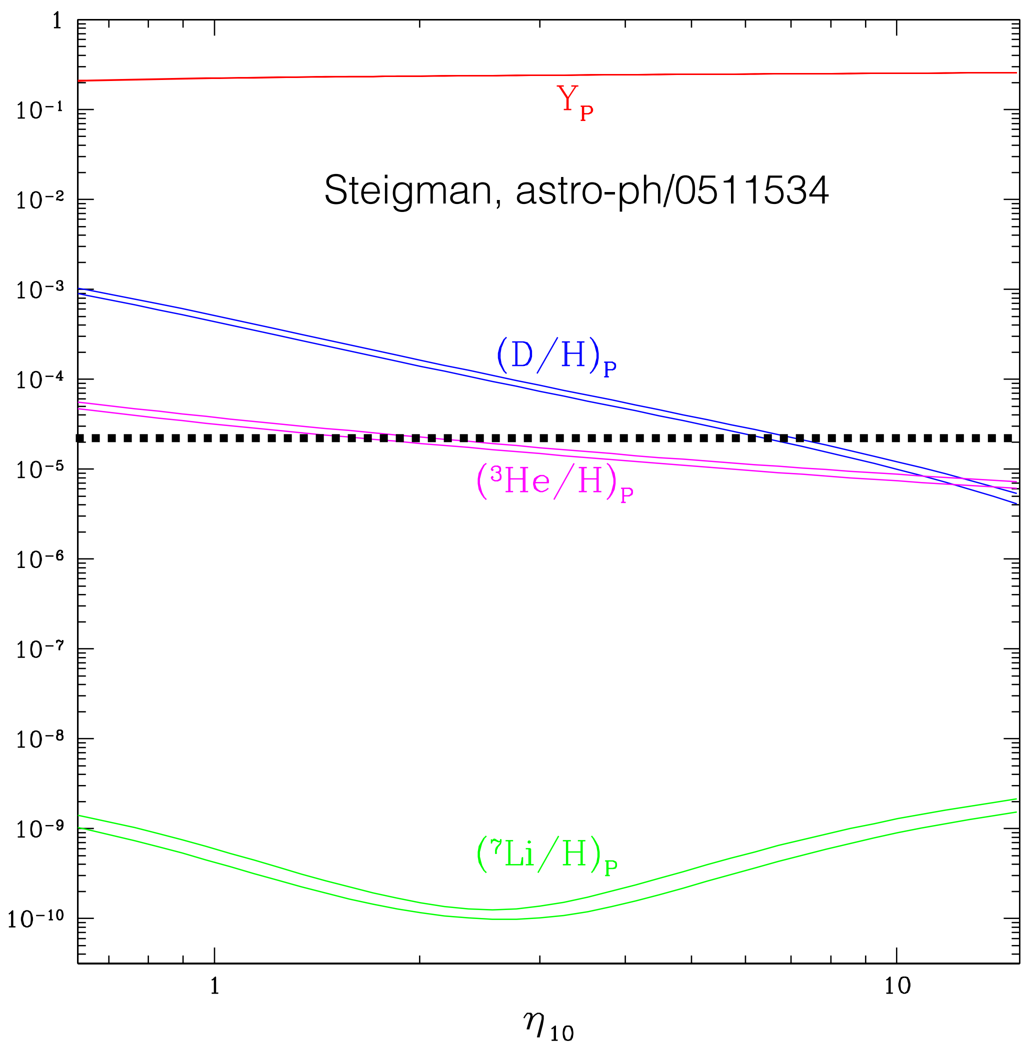

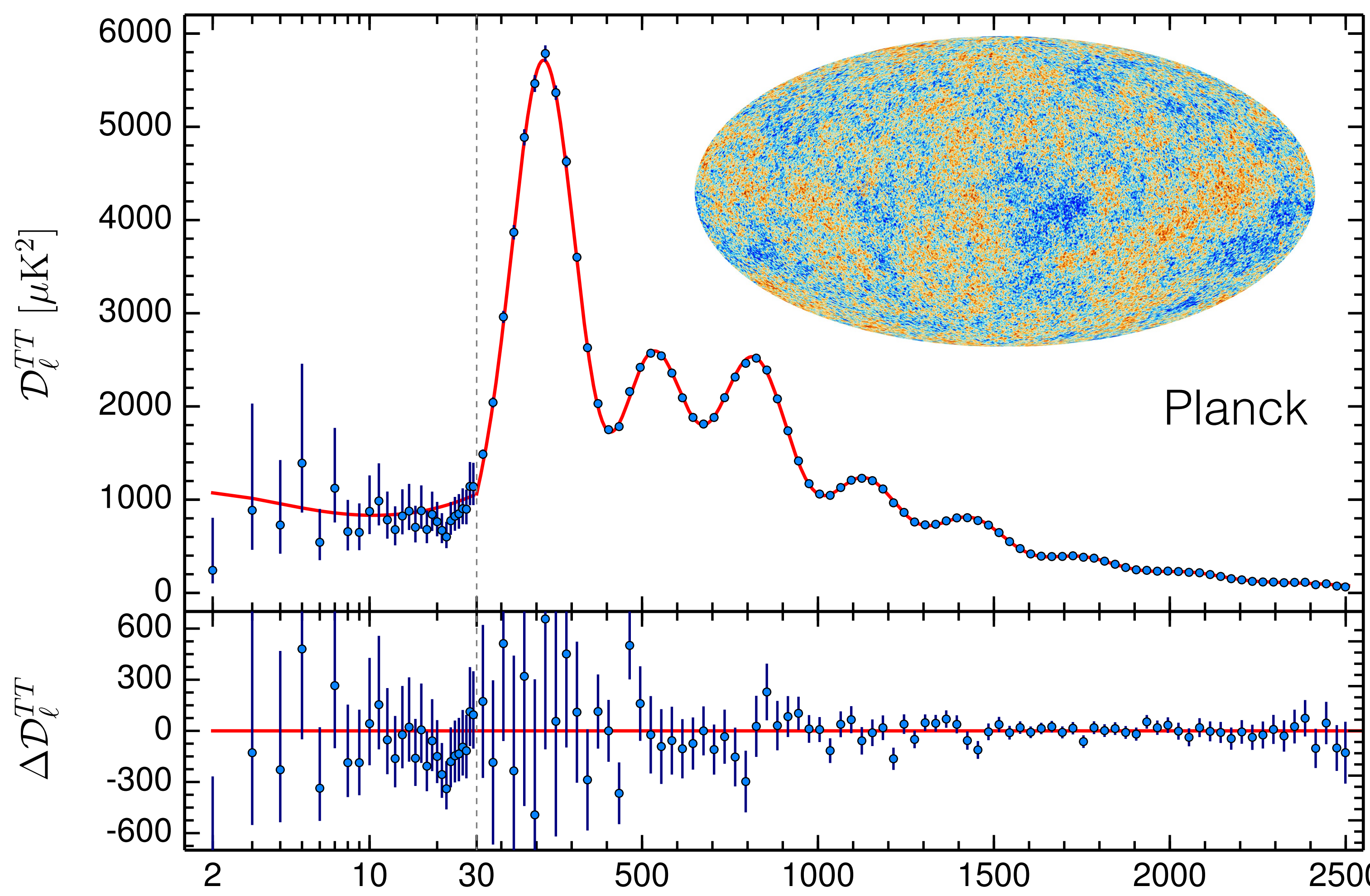

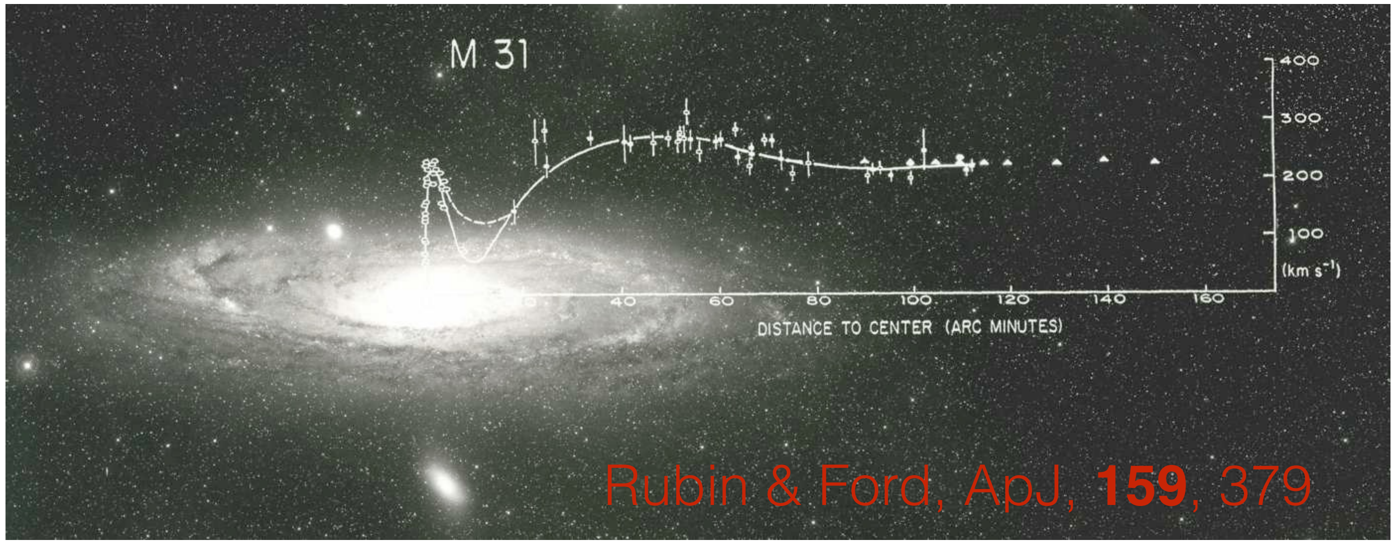

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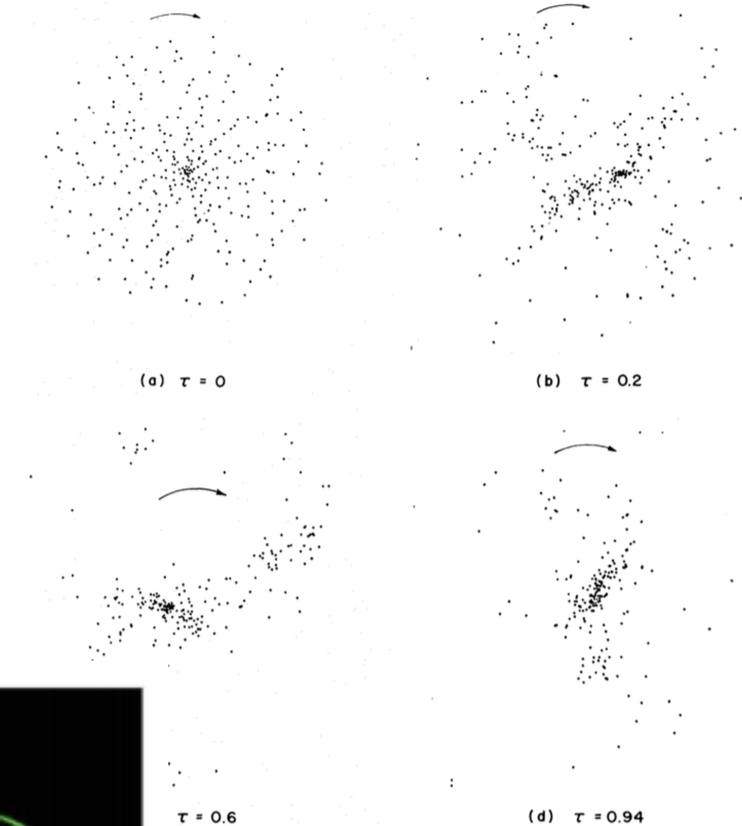
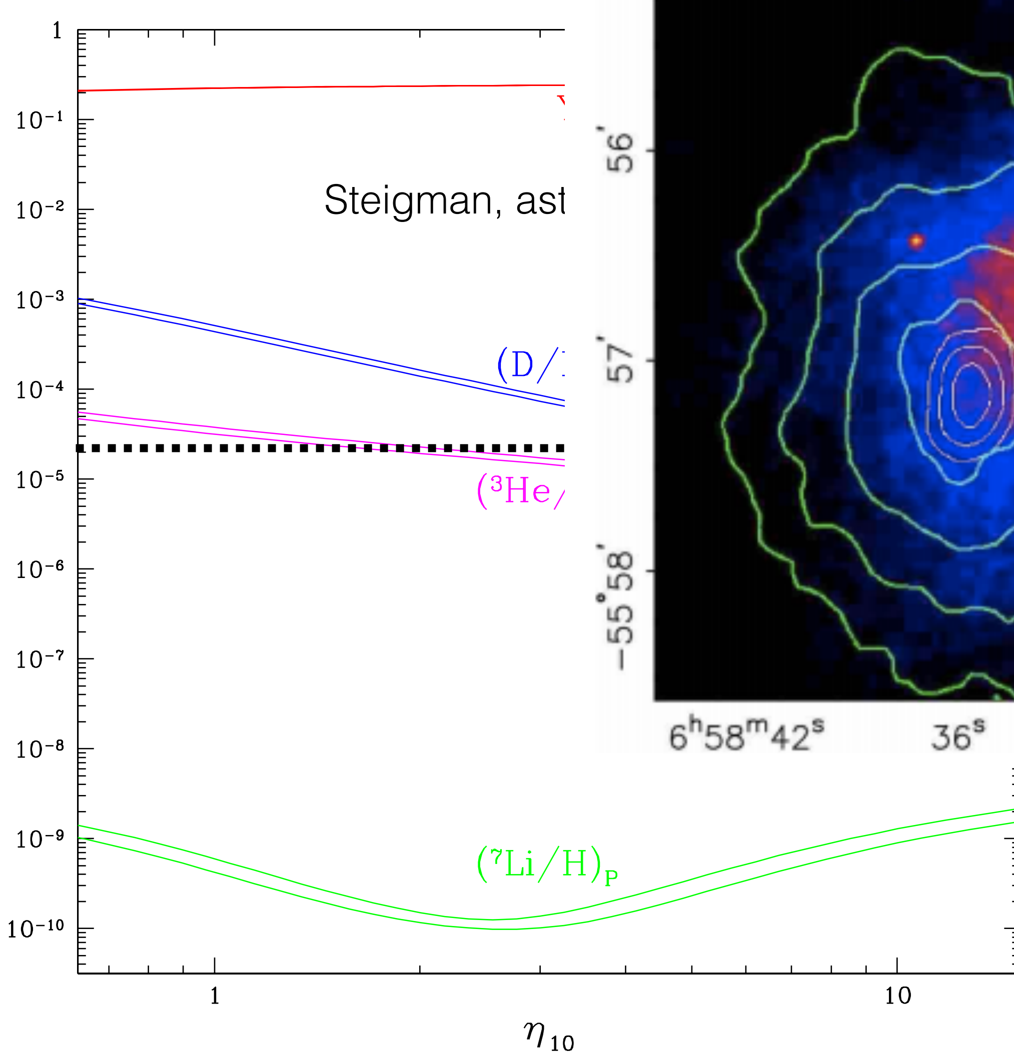
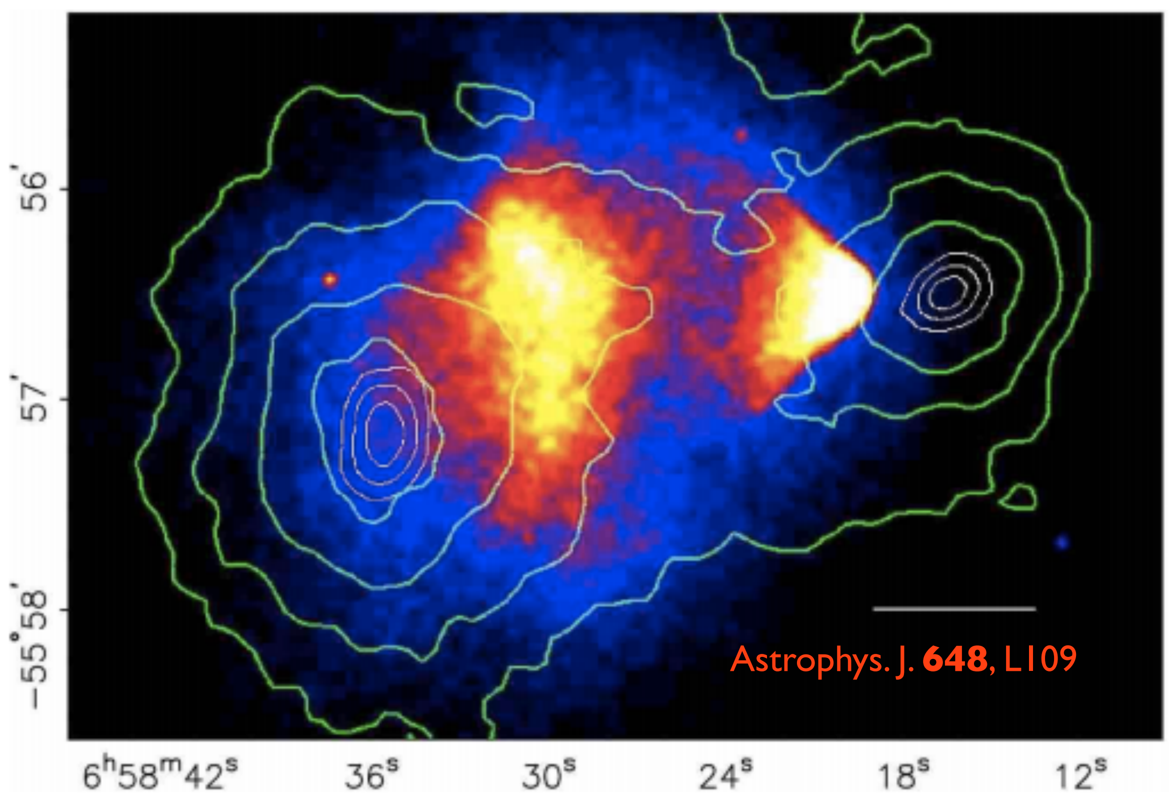
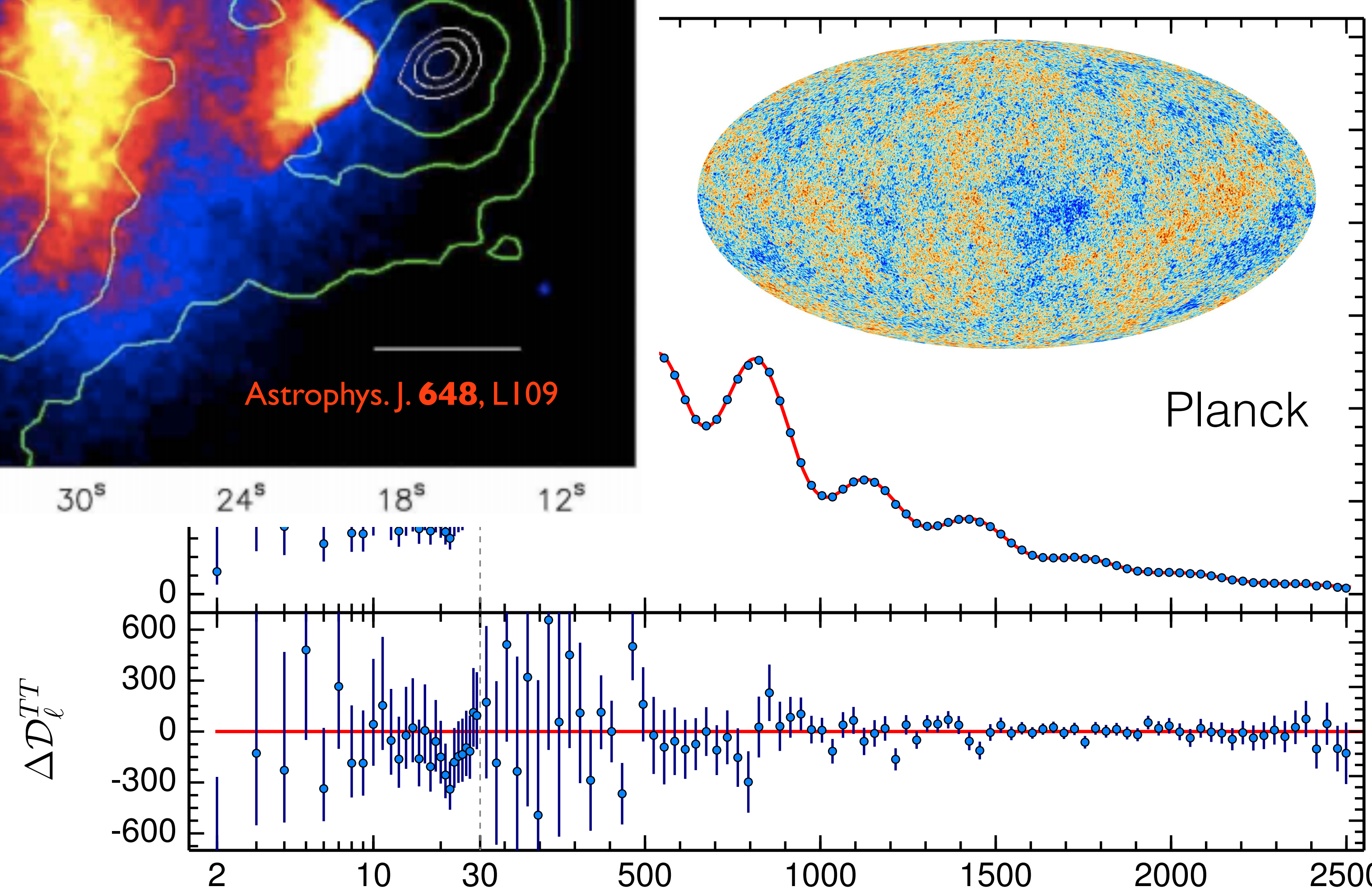


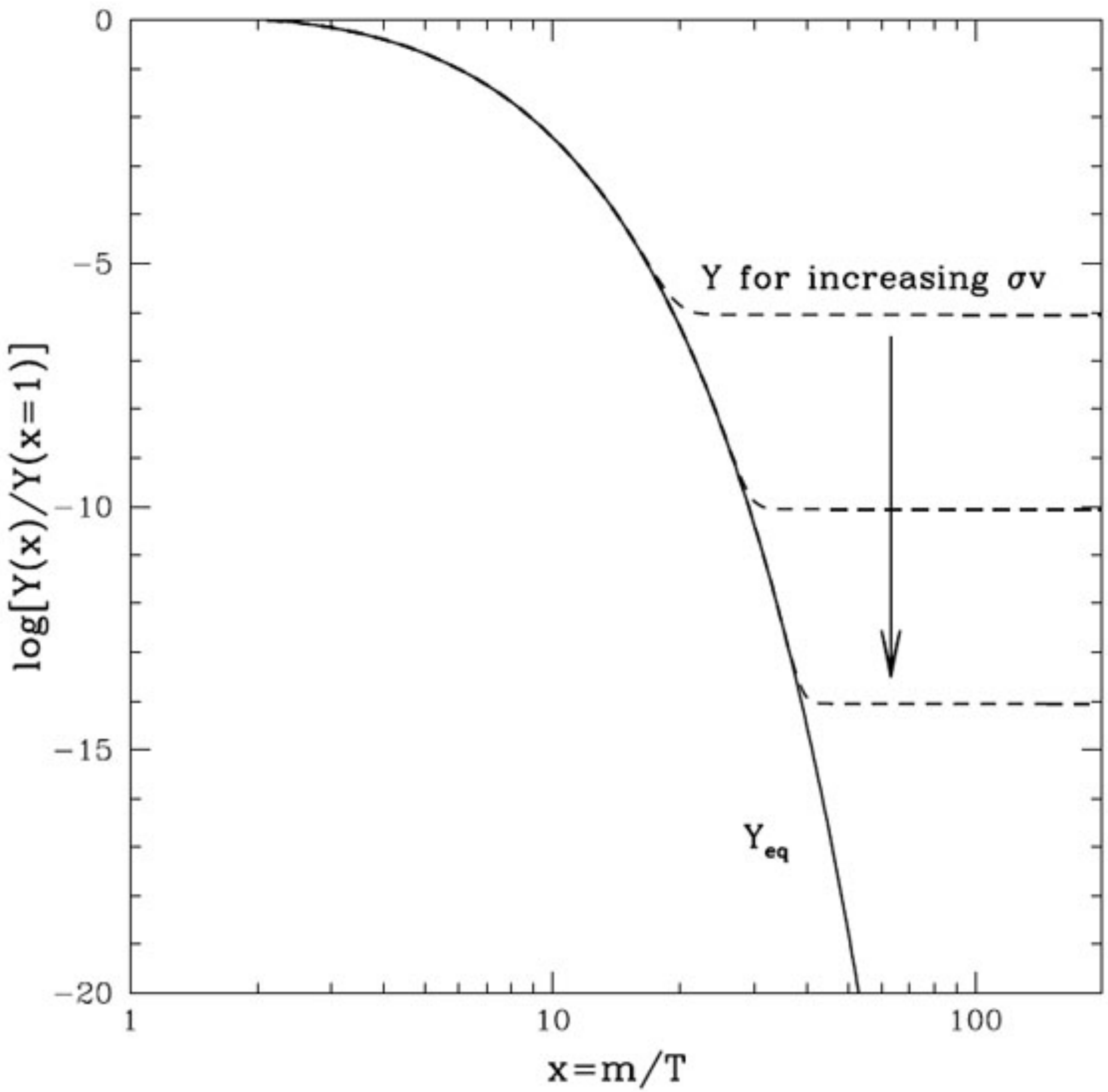




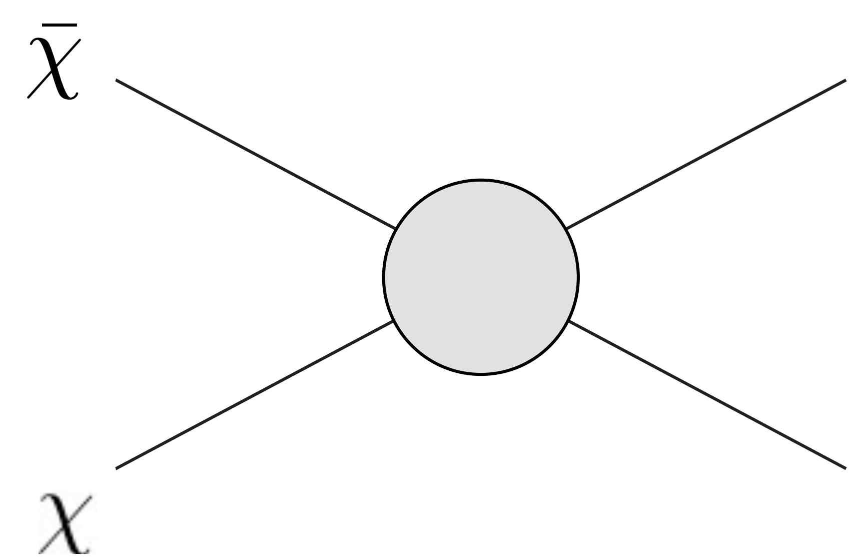


General consensus on energy budget of Universe

Consider thermal relic DM



Needs a coupling to light stuff



How do you generate that coupling

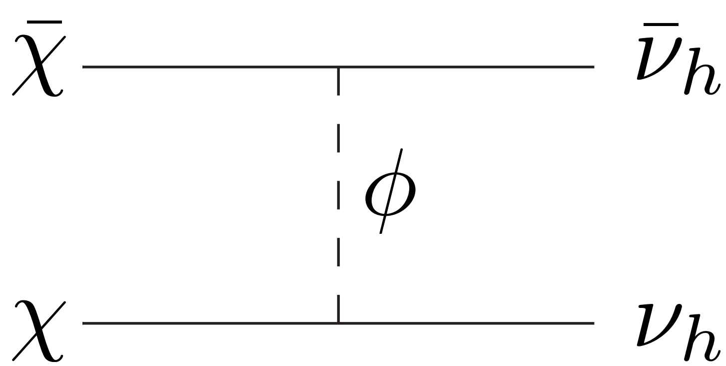
Basic Idea

$$\mathcal{L} \supset -\lambda \bar{L} H N - y \bar{N} \chi \phi + \text{h.c.} \to -\lambda v \bar{\nu} N - y \bar{N} \chi \phi + \text{h.c.}$$

$$\nu_l = \sqrt{1-U^2}\nu + UN$$

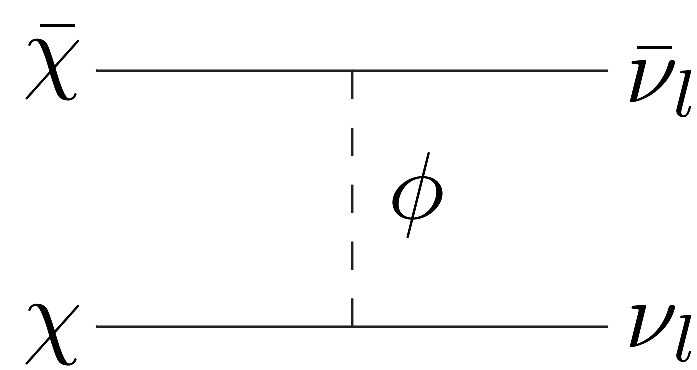
$$\nu_h = -U\nu + \sqrt{1-U^2}N$$

Case I: $m_\chi > M$



$\propto 1 - U^2$

Case II: $m_\chi < M$



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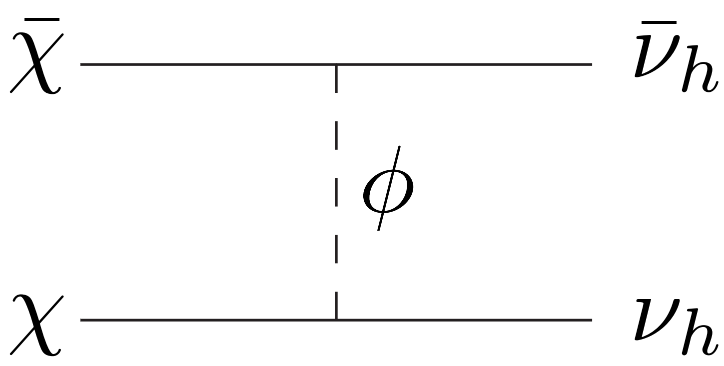

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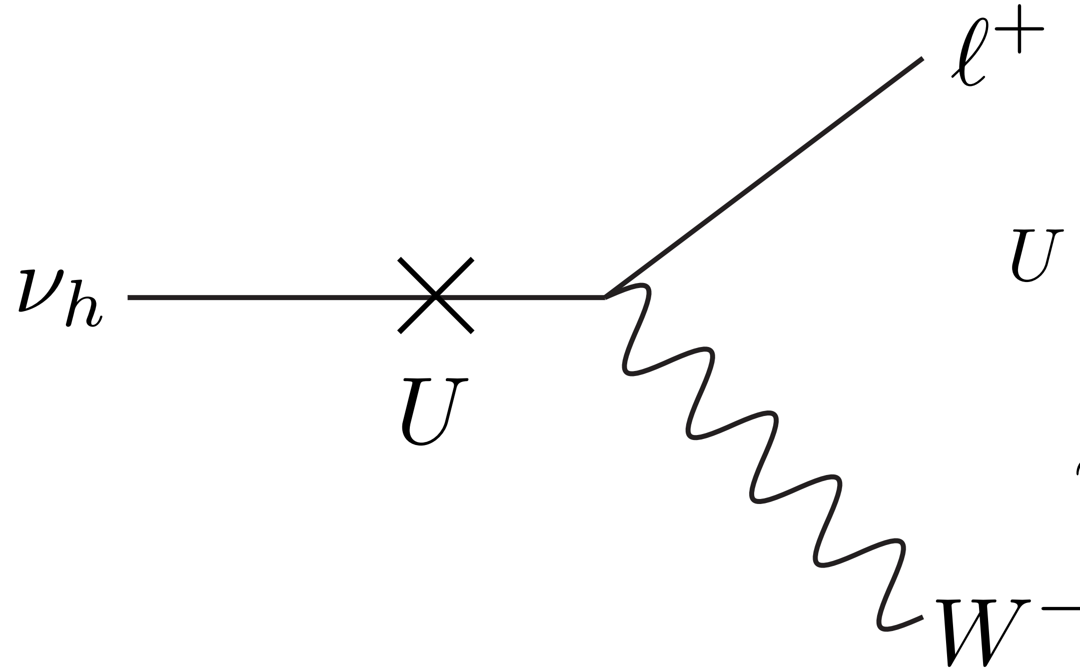
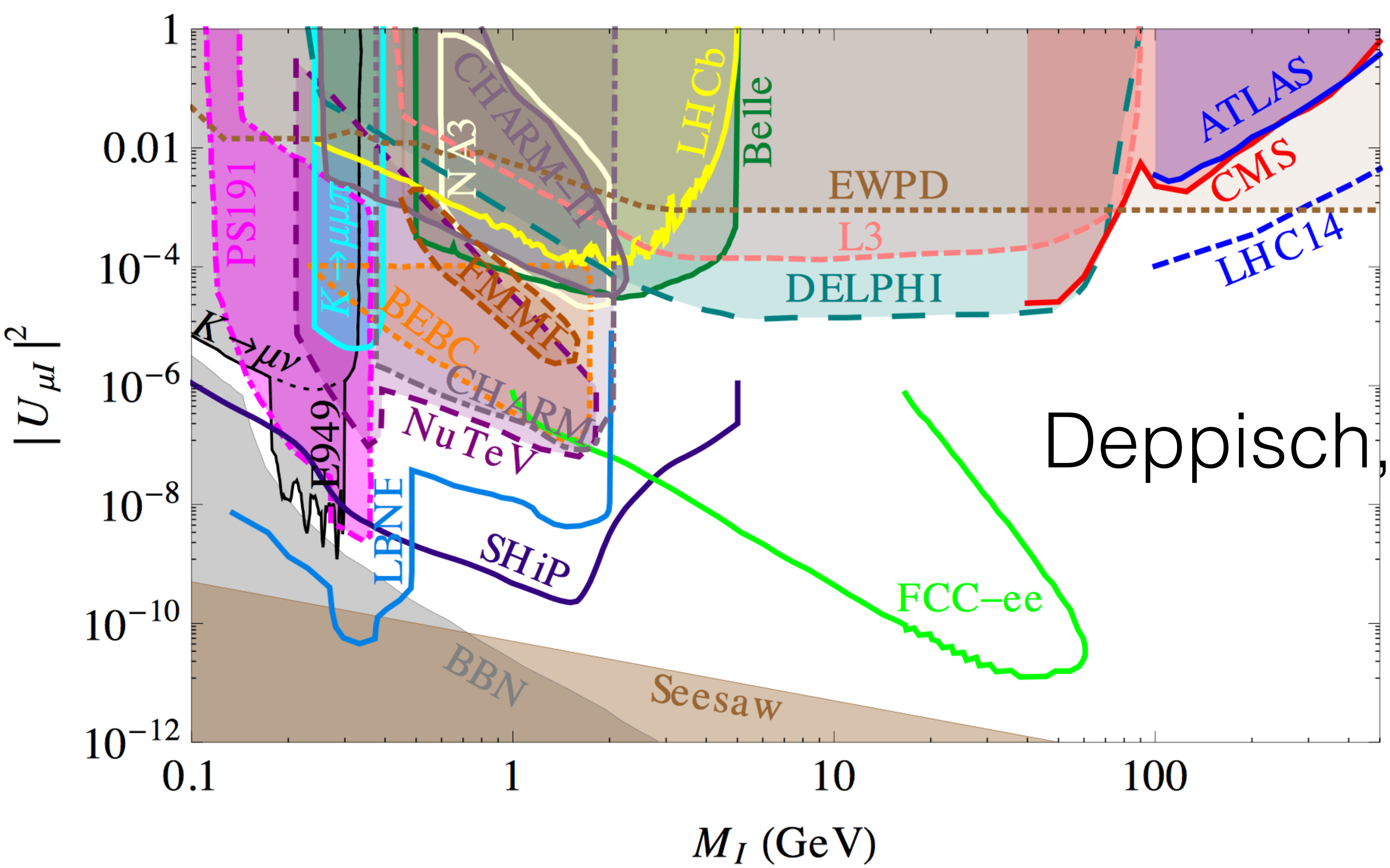


U can be small

$$U \sim \sqrt{\frac{m_l}{m_h}}$$

$$\sim 10^{-6}\sqrt{\frac{100\ \mathrm{GeV}}{m_h}}$$



Deppisch, Dev, Pilaftsis

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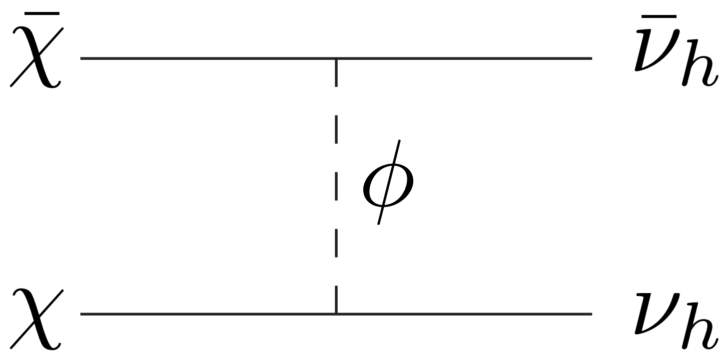

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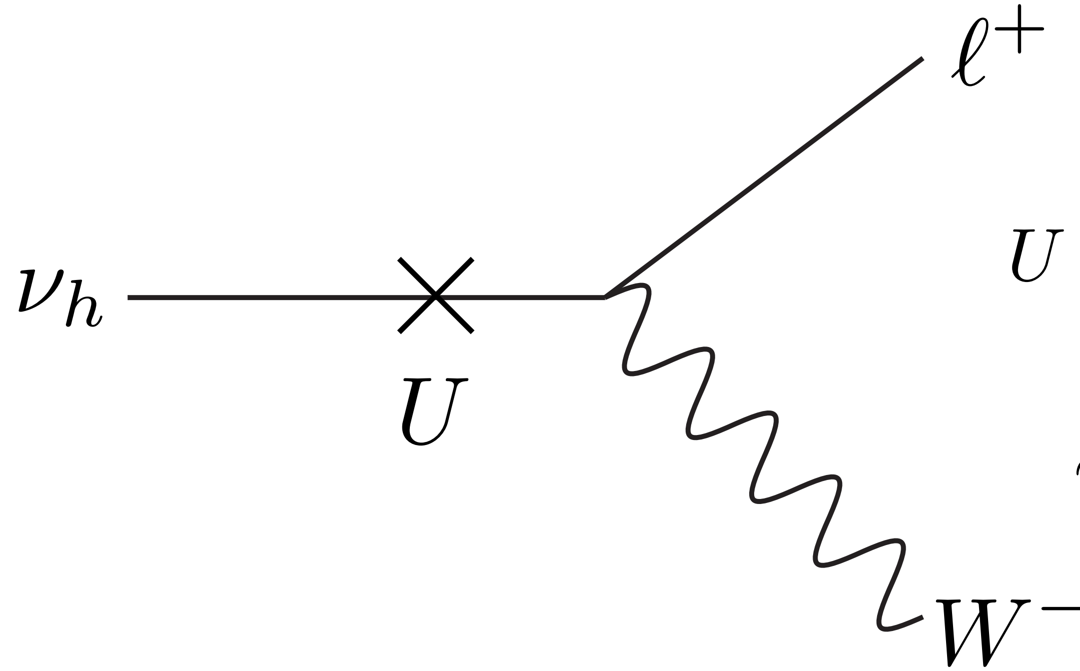

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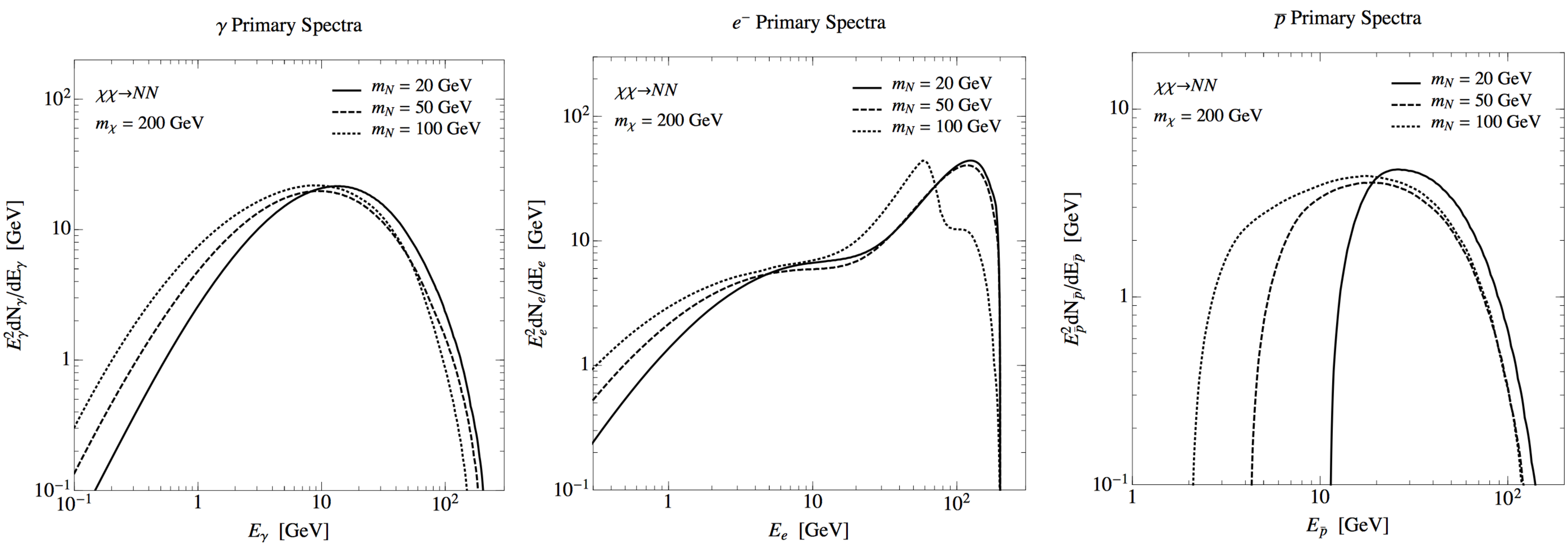

Batell, Han, & Shams Es Haghi 1704.08708

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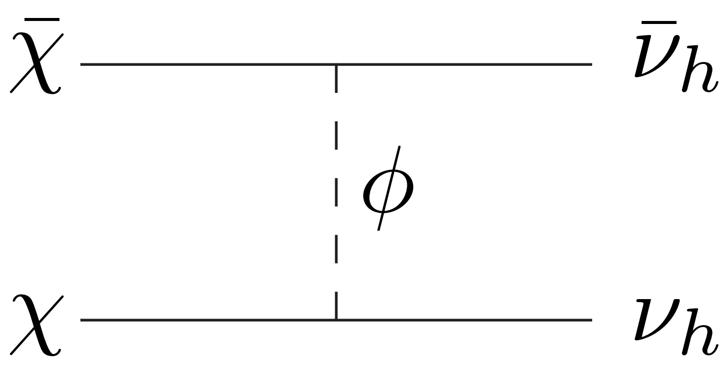

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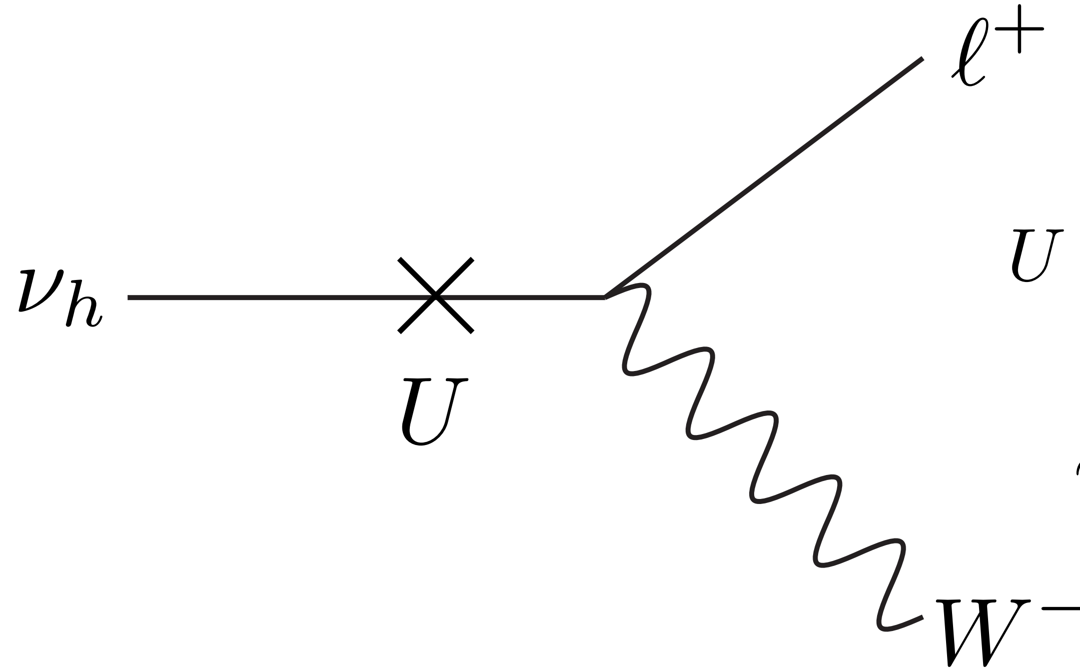

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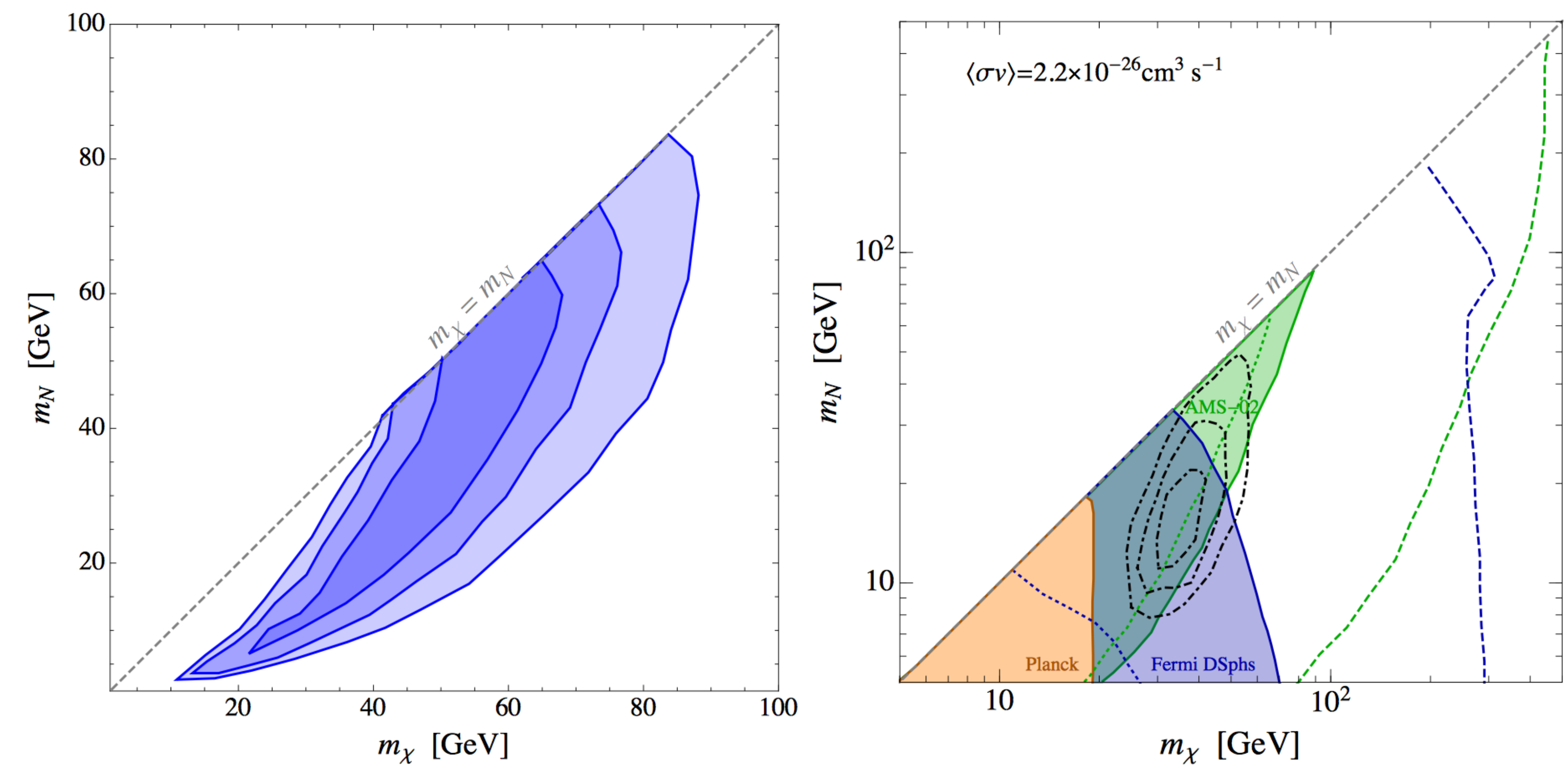
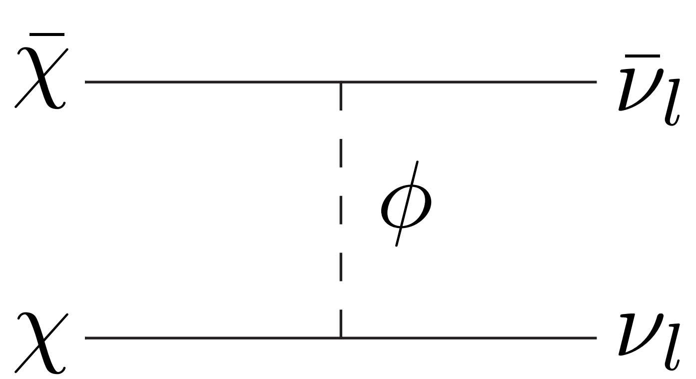


Batell, Han, & Shams Es Haghi 1704.08708

Case II: $m_\chi < M$



$\propto U^2$

$$\langle \sigma v \rangle = \frac{y^4 U^4}{32\pi} \frac{m_\chi^2}{m_\phi^4} \left(1 + \frac{m_\chi^2}{m_\phi^2}\right)^{-2}$$

$$\simeq 3 \times 10^{-26} \frac{\text{cm}^3}{\text{s}} \left(\frac{y\,U}{0.2}\right)^4 \left(\frac{m_\chi}{10\ \text{GeV}}\right)^{-2} \left(\frac{m_\phi/m_\chi}{3}\right)^{-4}$$

Requires large mixing angle!

Minimal Model

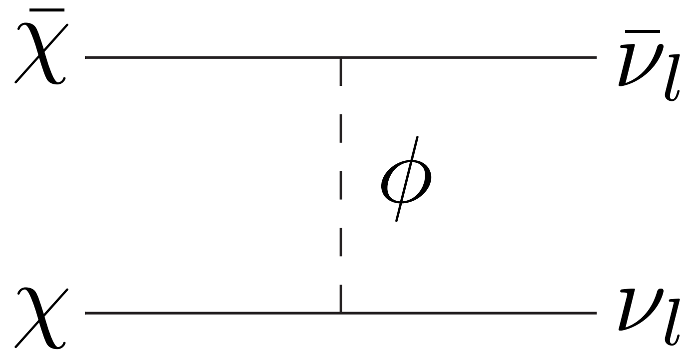
$$\mathcal{L} \supset -\lambda_i \bar{L}_i H N_R - M_N \bar{N}_L N_R - \phi \bar{\chi} \left(y_L N_L + y_R N_R\right) + \text{h.c.}$$

$$\to -\lambda_i v \bar{\nu}_{iL} N_R - M_N \bar{N}_L N_R - \phi \bar{\chi} \left(y_L N_L + y_R N_R\right) + \text{h.c.}$$

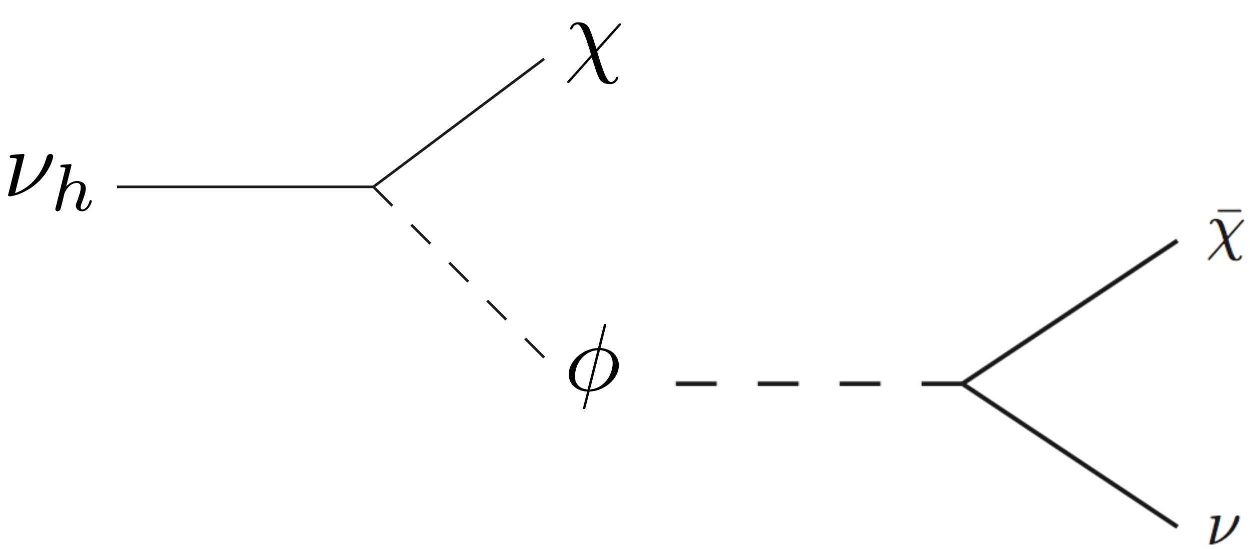
lepton number conserved (for small ν masses & large mixing)

Bertoni, Ipek, DM, & Nelson 1412.3113
Batell, Han, DM, & Shams Es Haghi *in prep.*

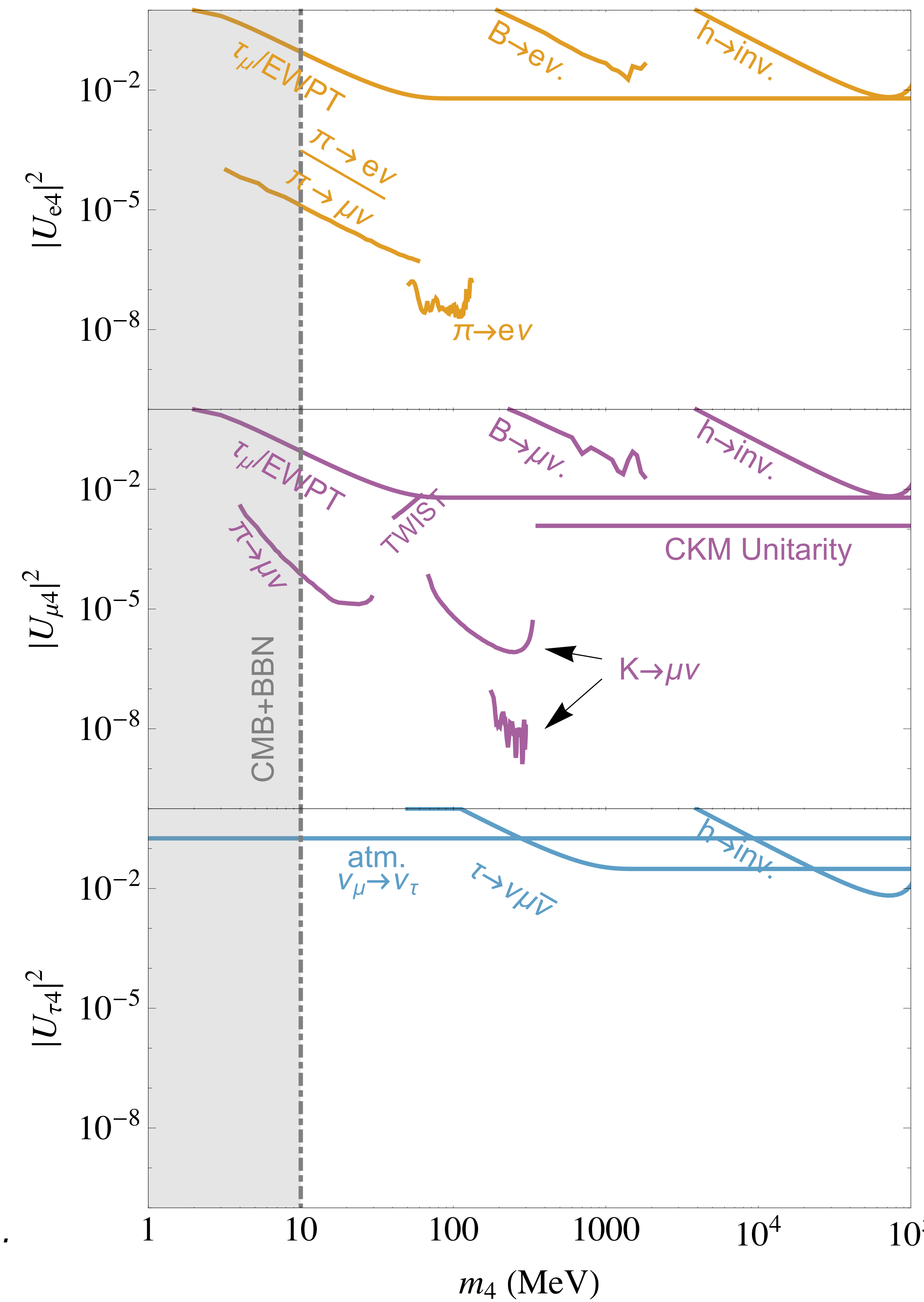
Case II: $m_\chi < M$



$\propto U^2$

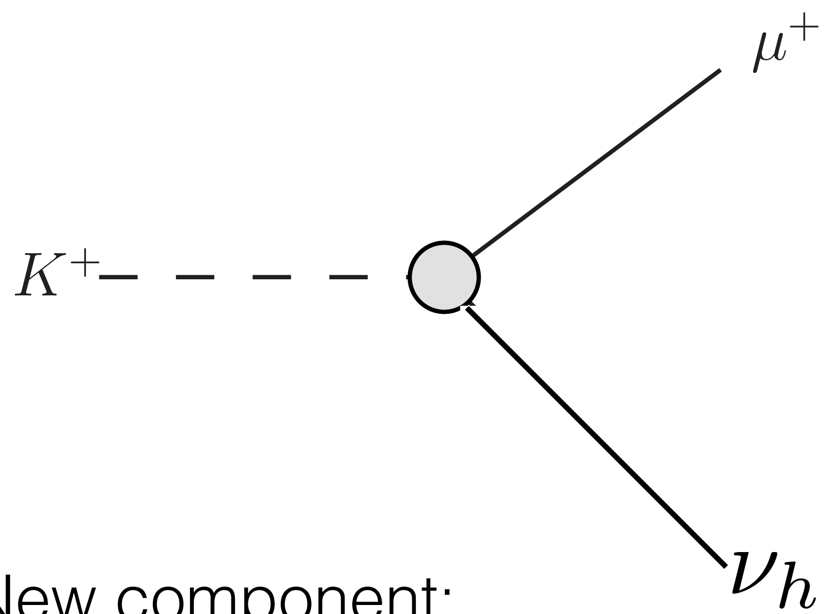


heavy neutrino decays invisibly!

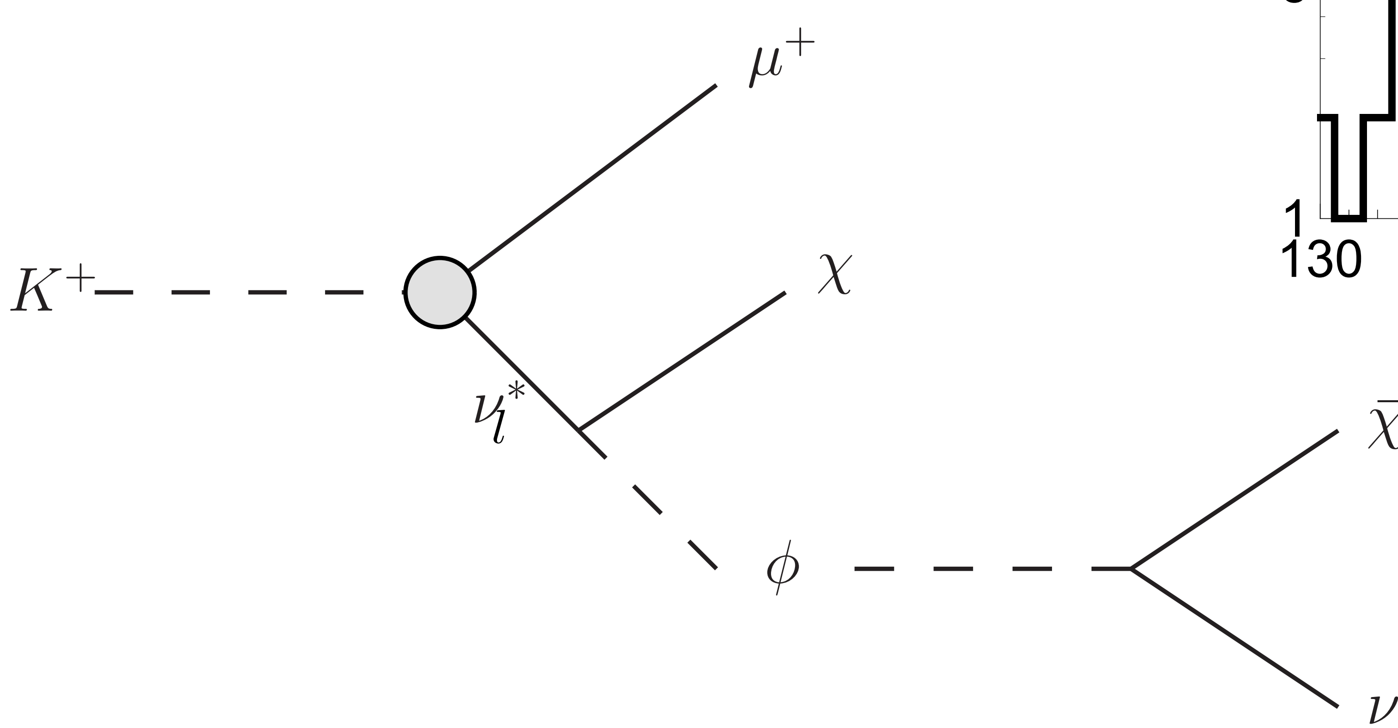


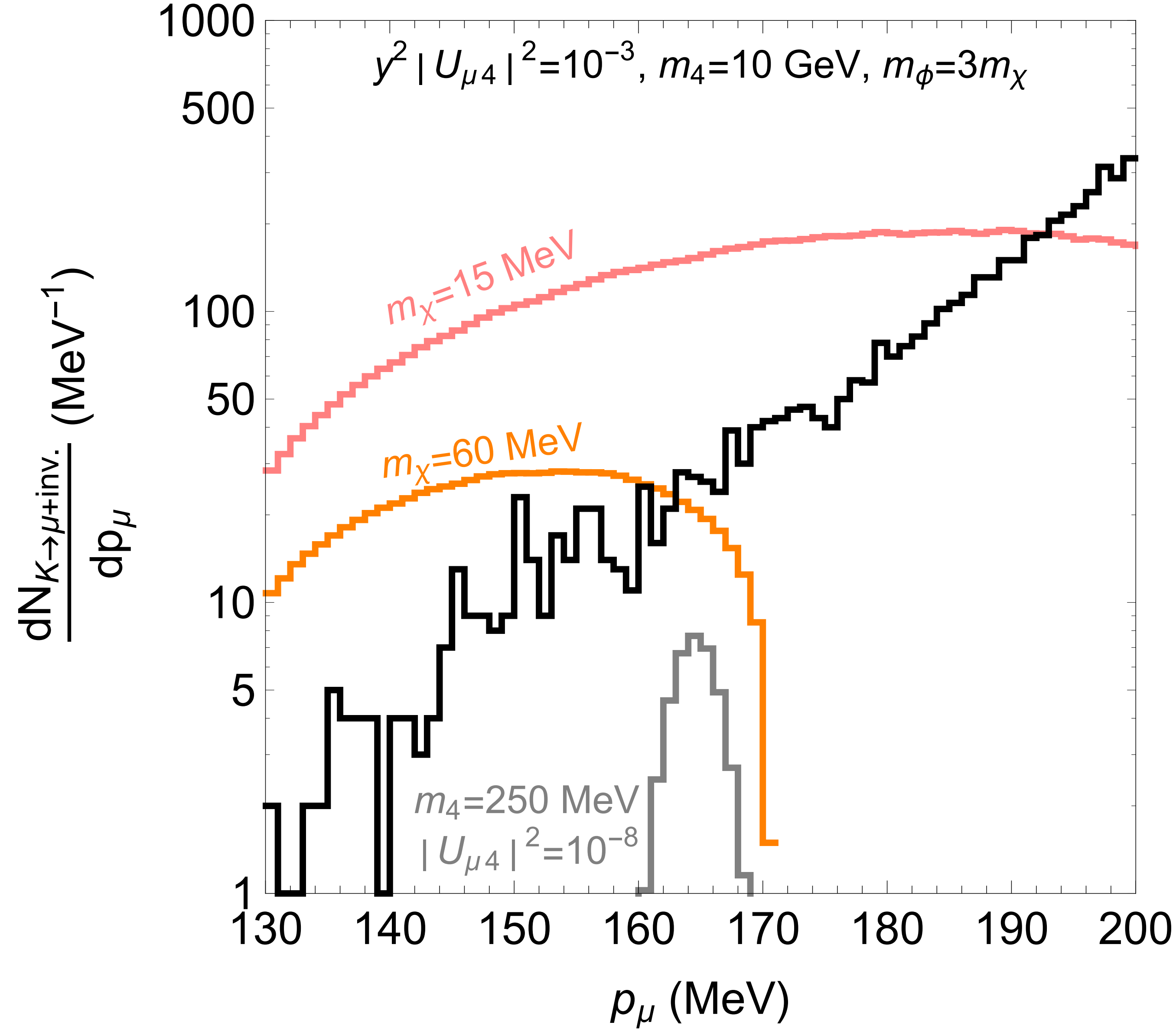
Bertoni, Ipek, DM, & Nelson 1412.3113
Batell, Han, DM, & Shams Es Haghi *in prep.*

Meson decays



New component:





E949: 10^{12} kaons

NA62 increase by ~order of mag.

Atmospheric Neutrino Oscillations

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

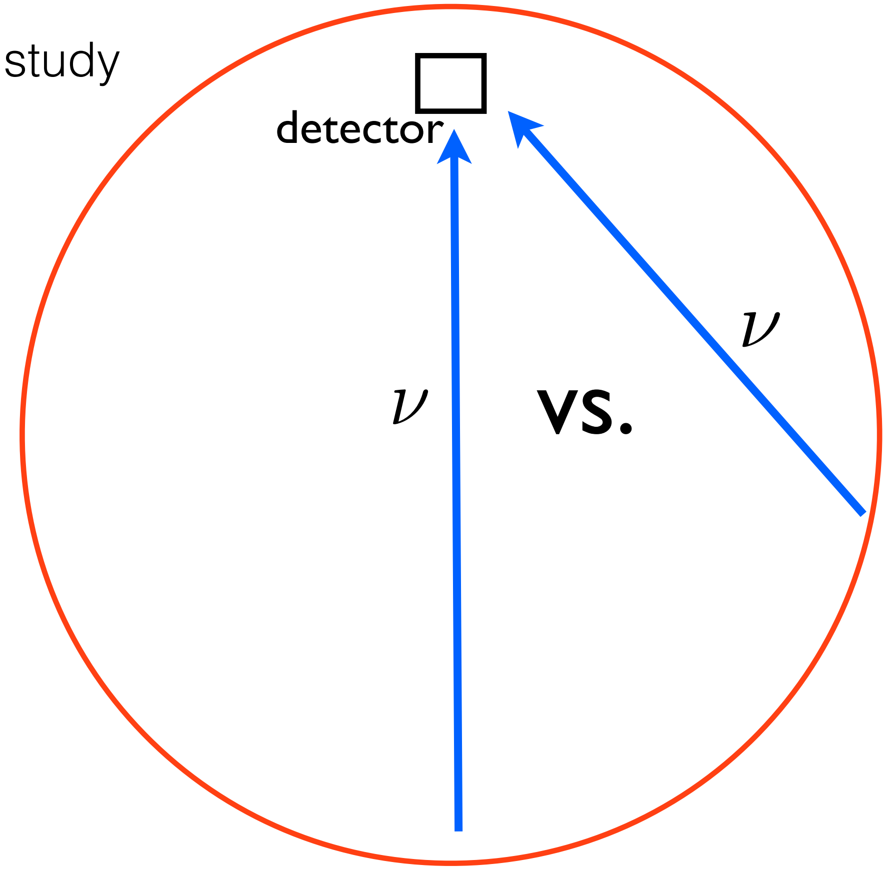
$$H = \left(\frac{\Delta m^2}{4E}\right)\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \begin{pmatrix} V_\mu & 0 \\ 0 & V_{\tau N} \end{pmatrix}$$

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

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

[Non-standard int.
$$\epsilon_{\tau\tau} = \frac{1}{6}\left(\frac{V_{\tau N}}{V_{\text{nc}}} - 1\right) = \frac{\sin^2\theta_\tau}{6}$$
]

see de Gouvea for DUNE study



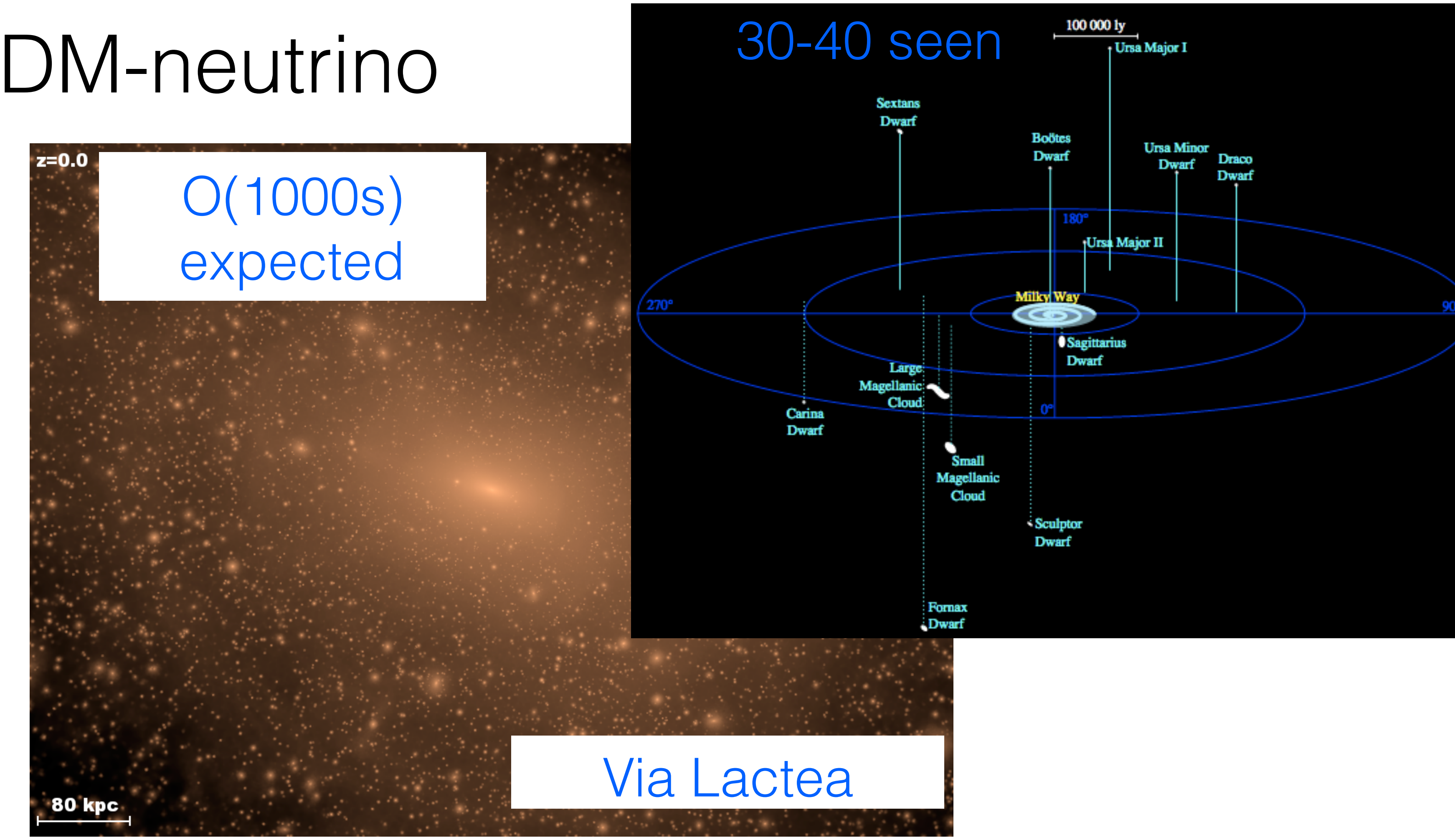
Oscillation pattern depends on amount of matter traversed

Super-K, arXiv:1410.2008

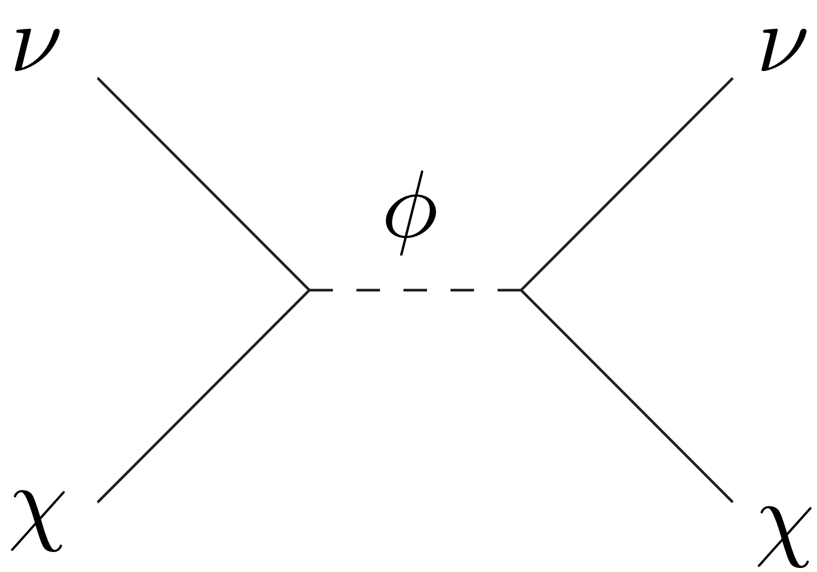
$\sin\theta_\tau < 0.42$ (stat. limited!)

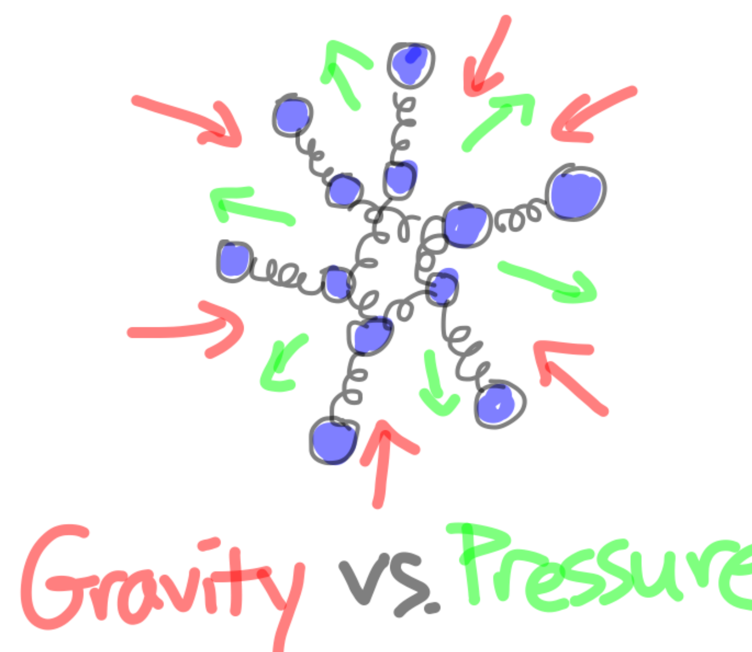
Are there hints for DM-neutrino interactions?

Count satellites of Milky Way galaxy:



DM-scattering on neutrinos

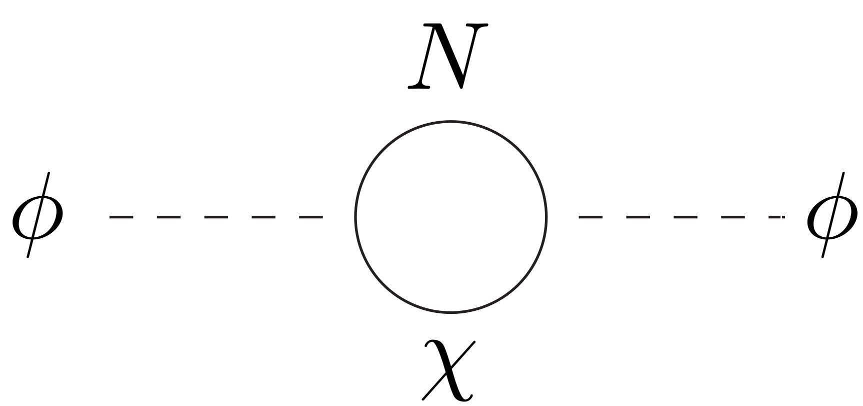




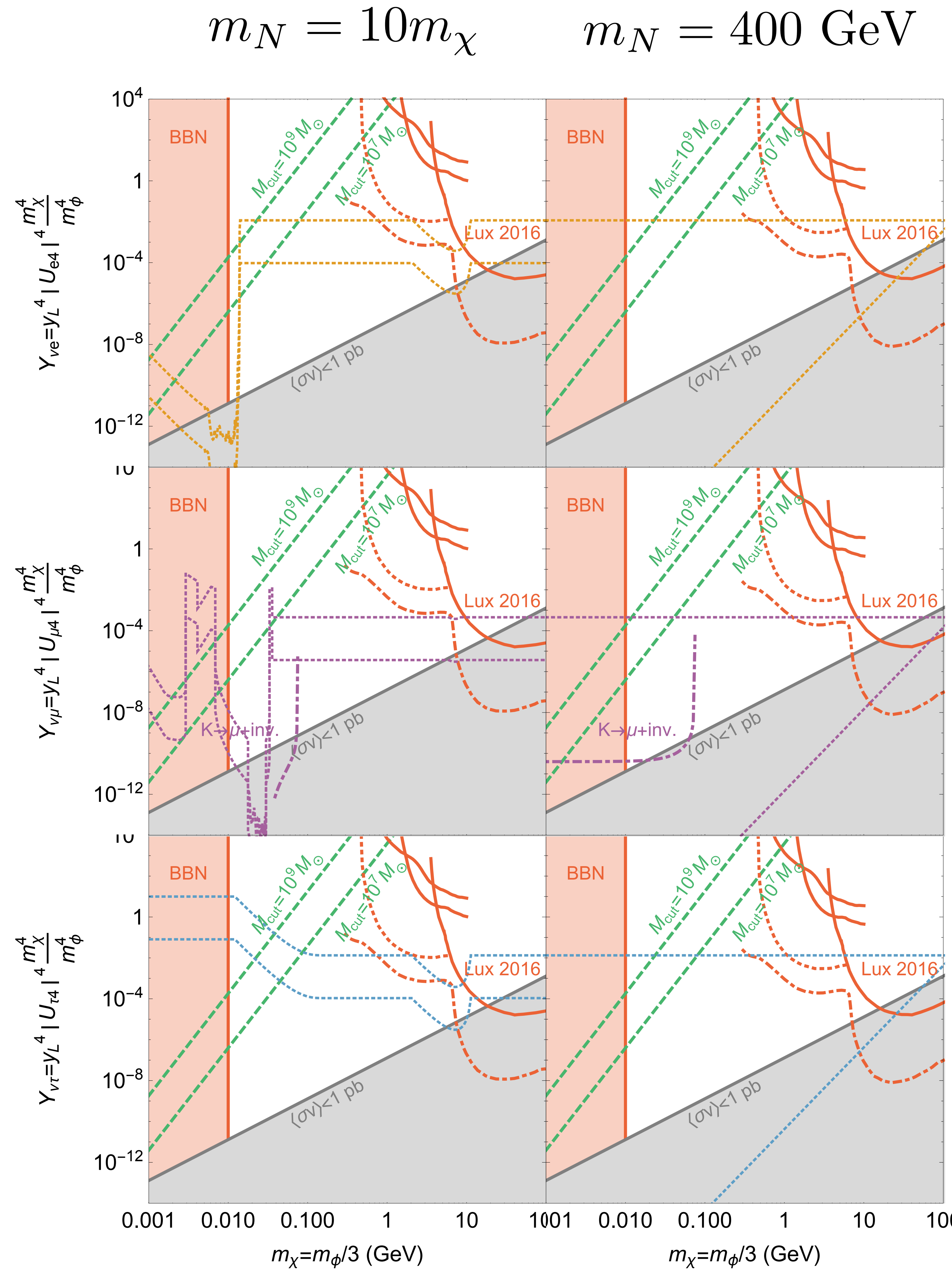
Boehm et al.
van den Aarssen et al.
Shoemaker et al.
Bertoni, Ipek, DM, & Nelson
Hooper, Kaplinghat, Strigari, & Zurek

Can summarize using particular combination of couplings:

$$Y \equiv y_L^4 \left(\sum_i |U_{i4}|^2 \right)^2 \frac{m_\chi^4}{m_\phi^4} = 32\pi m_\chi^2 \langle \sigma v \rangle$$



$$\delta m_\phi^2 \sim \frac{y^2}{16\pi^2} m_N^2$$



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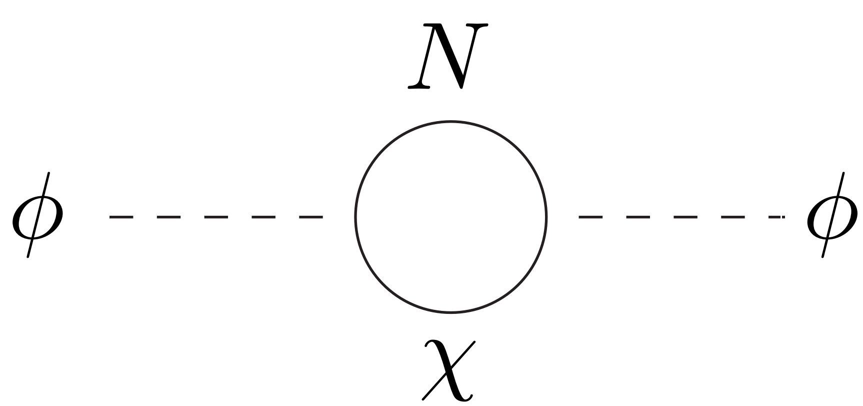

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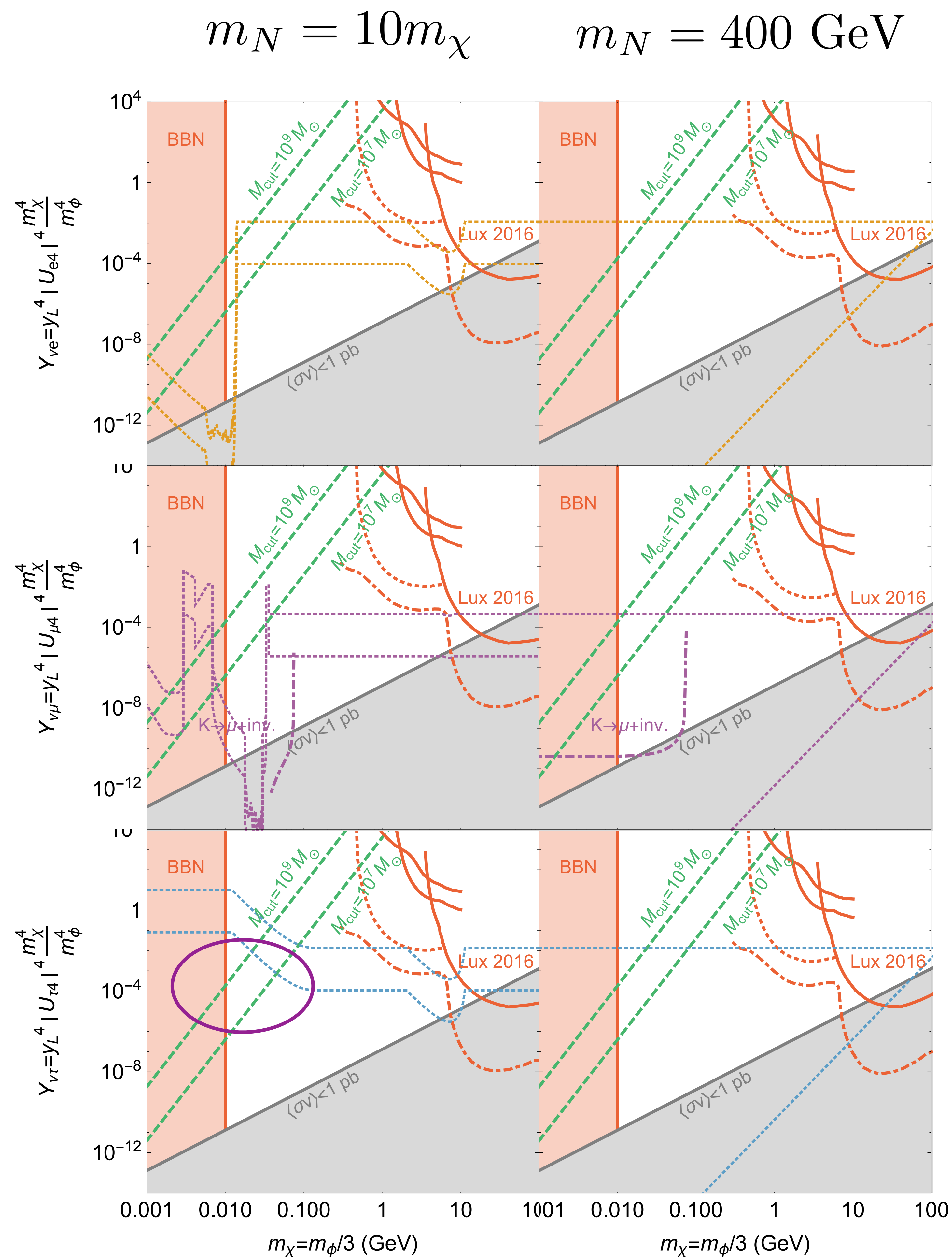


Neutrino Oscillations when large tau mixing

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

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

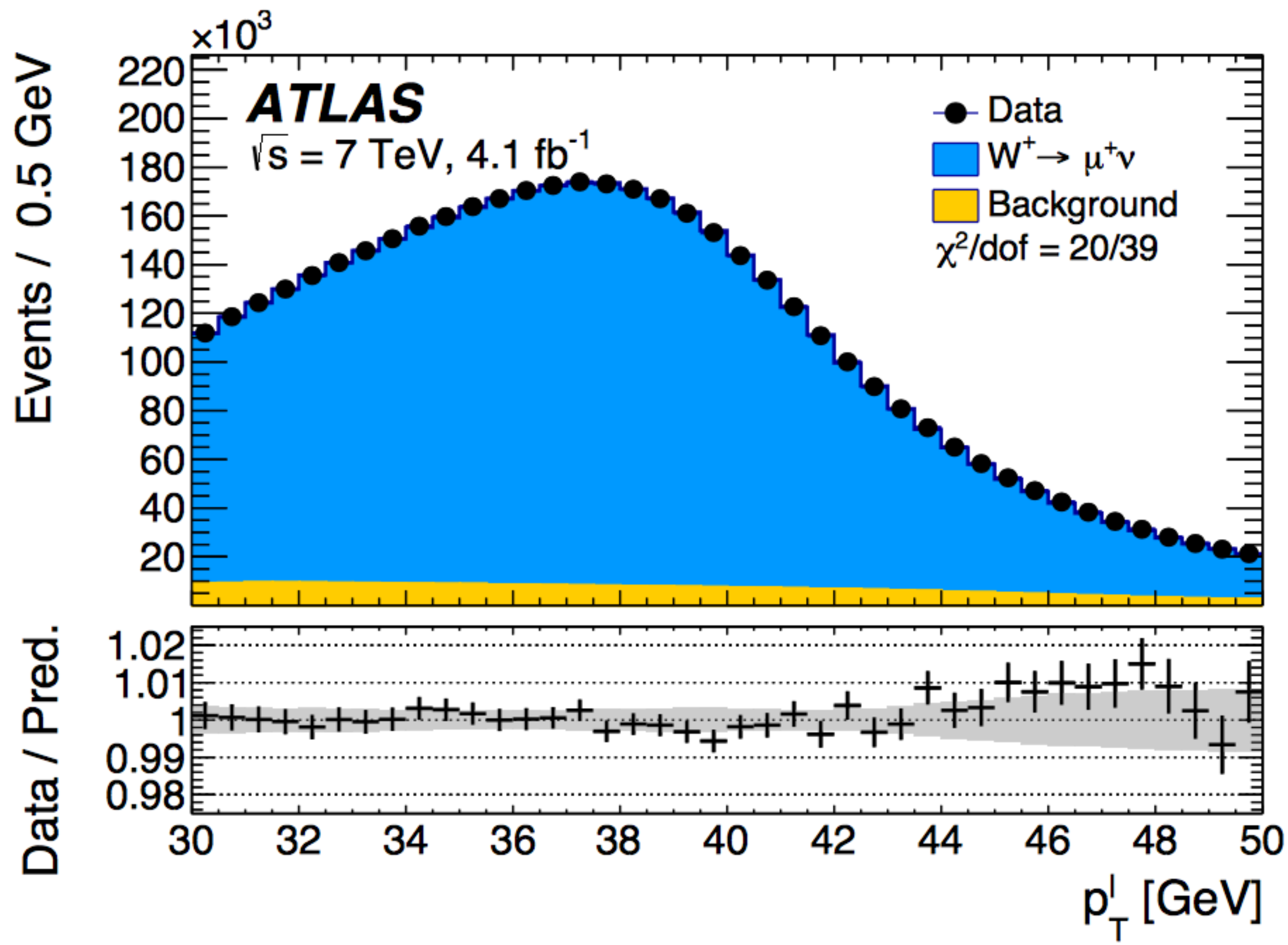
$\Rightarrow$ Solar neutrinos potentially sensitive

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

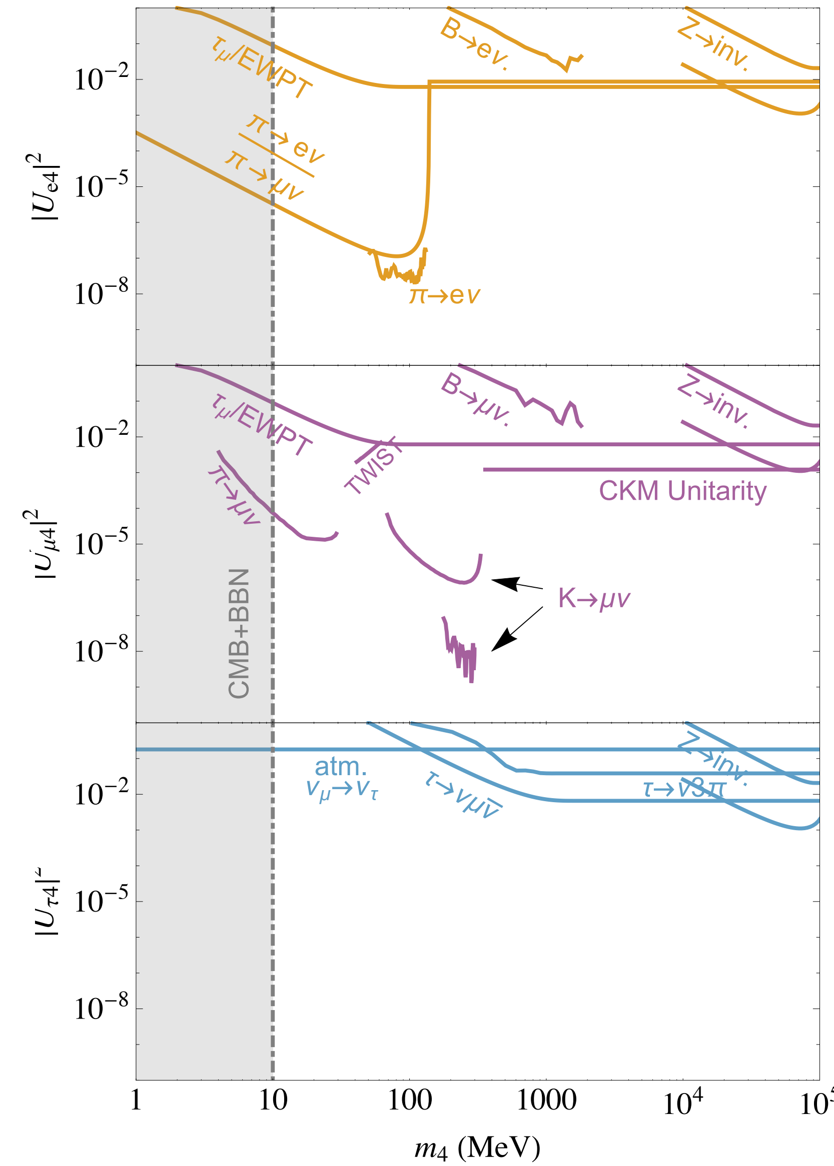
$\sin\theta_\tau < 0.6$

In progress…

ATLAS W mass measurement 1701.07240

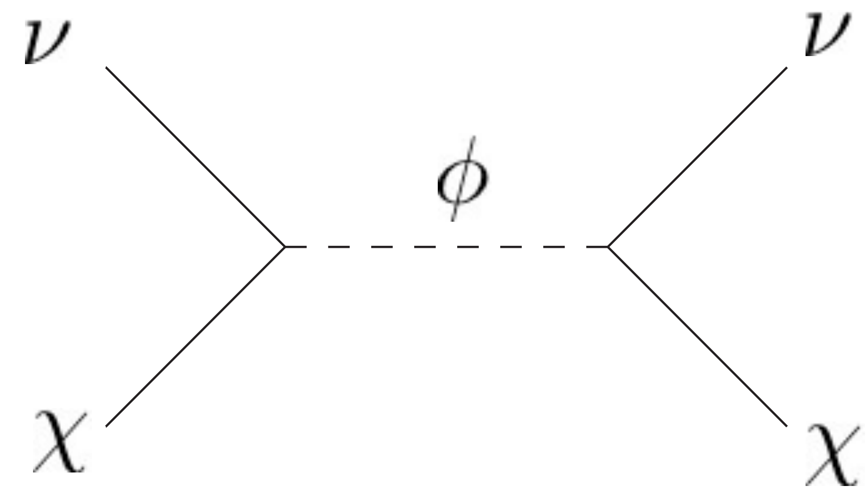


$\sim 2U^2$

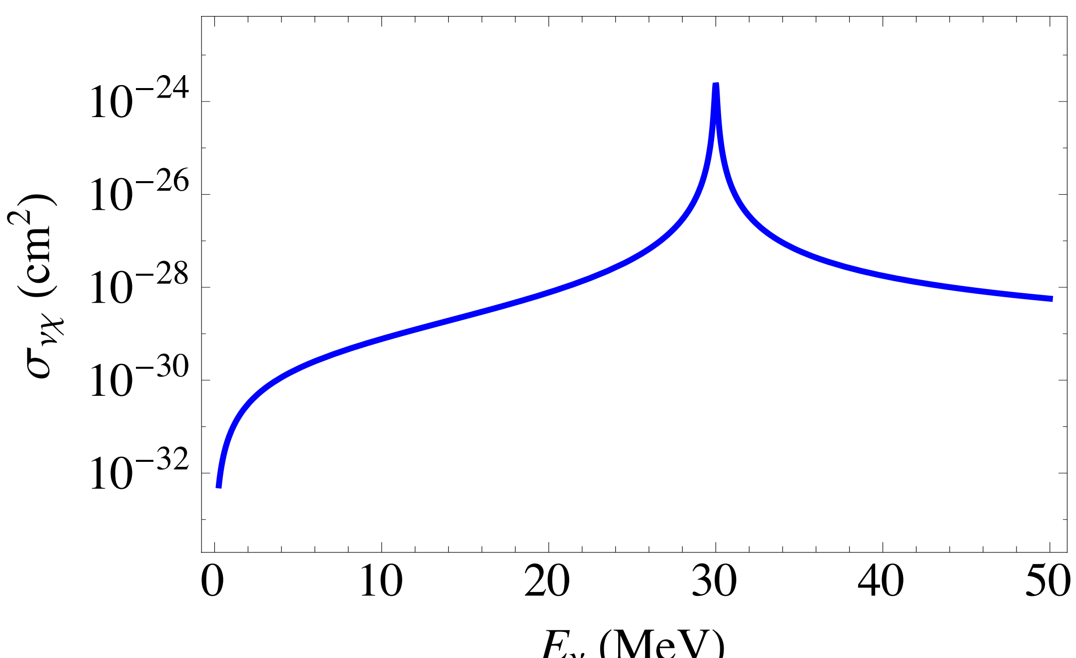


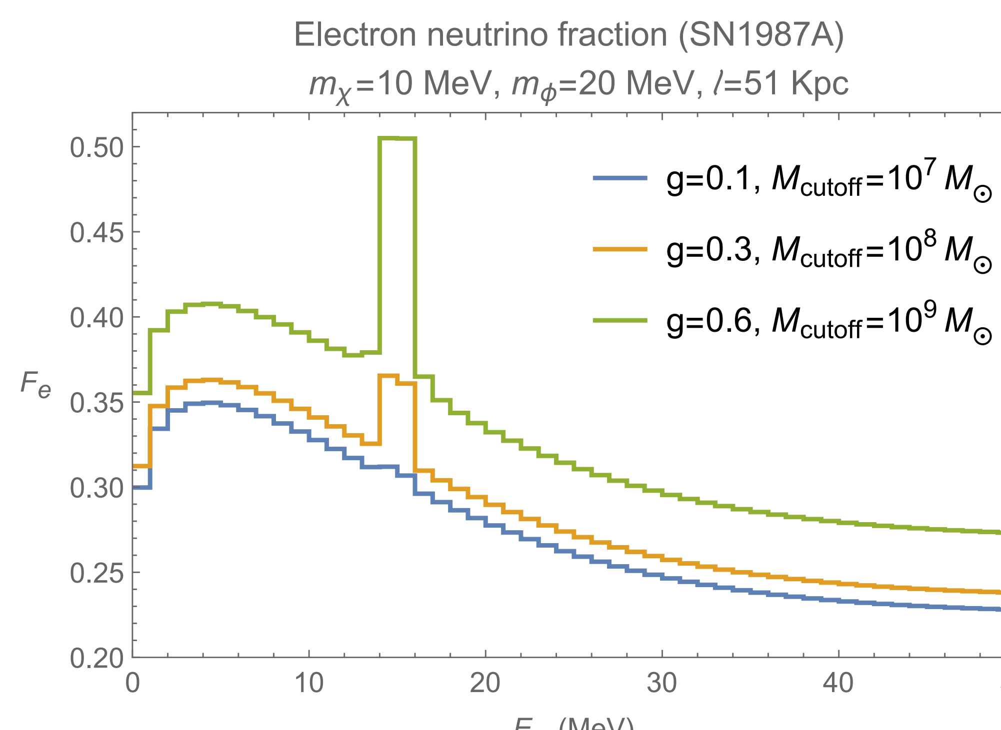
Neutrinos from Supernovae

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





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

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

(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 $m_\chi > 10 \text{ MeV}$

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

(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?

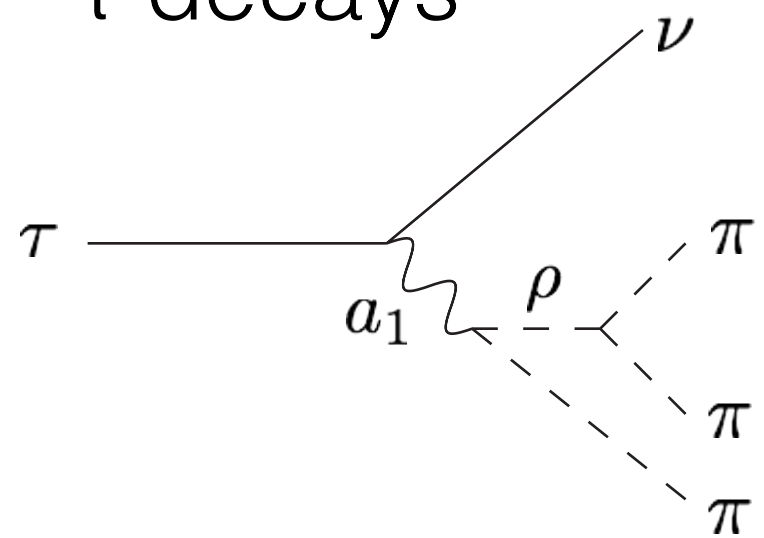
What are effects of flavor?

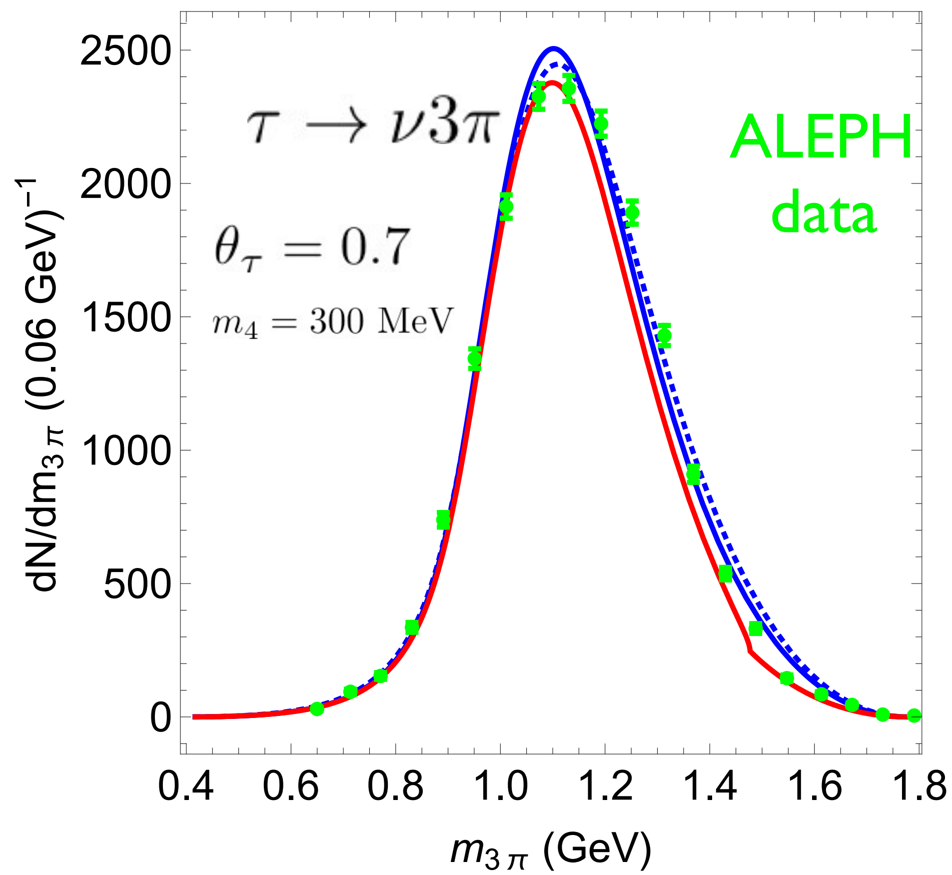
Could ν “dwell” time be increased?

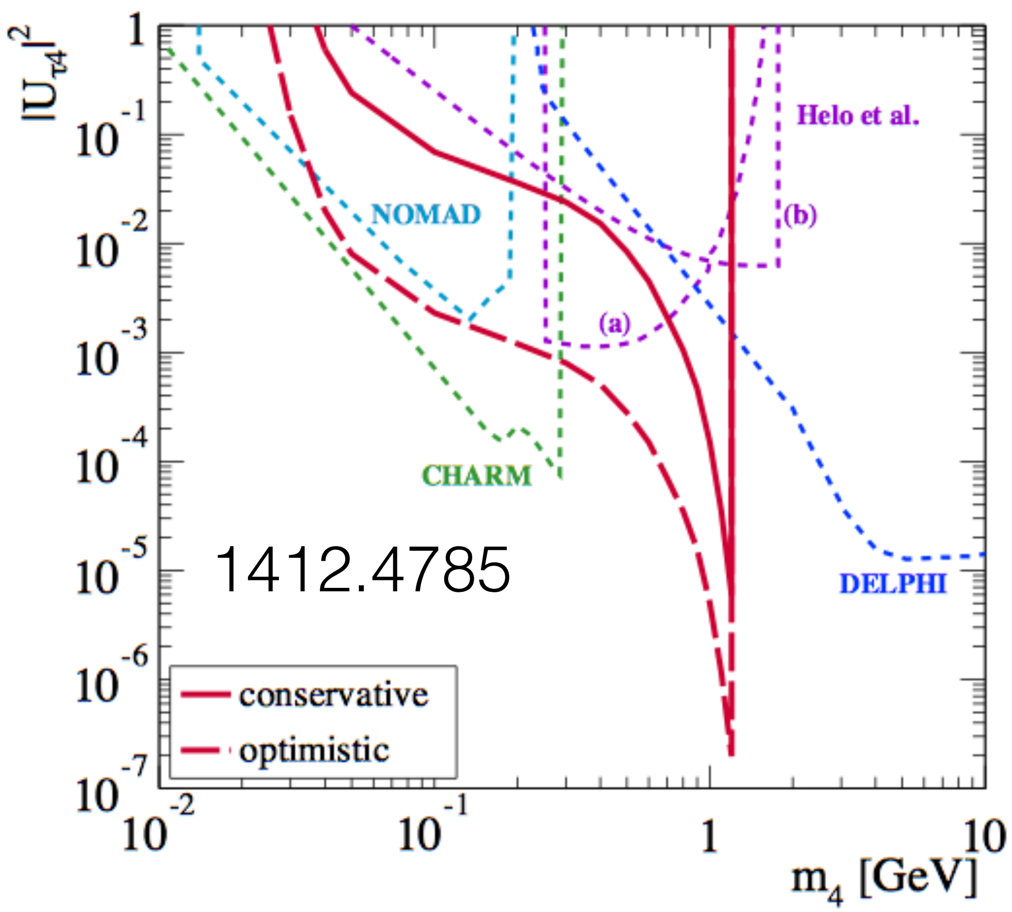
Very complicated…

Future tests

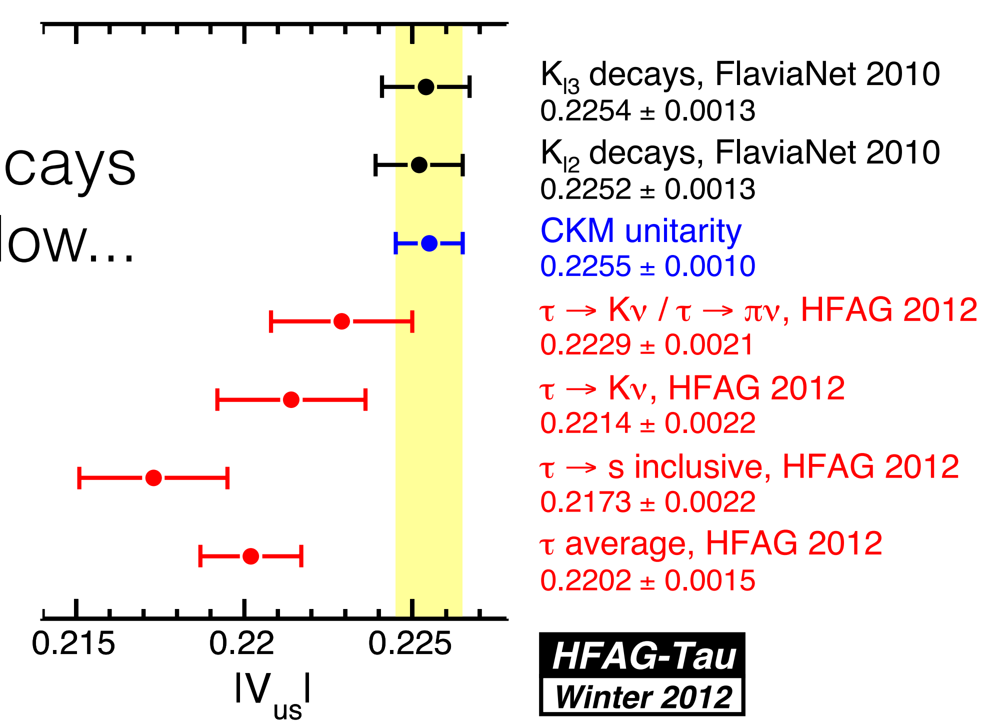
τ decays



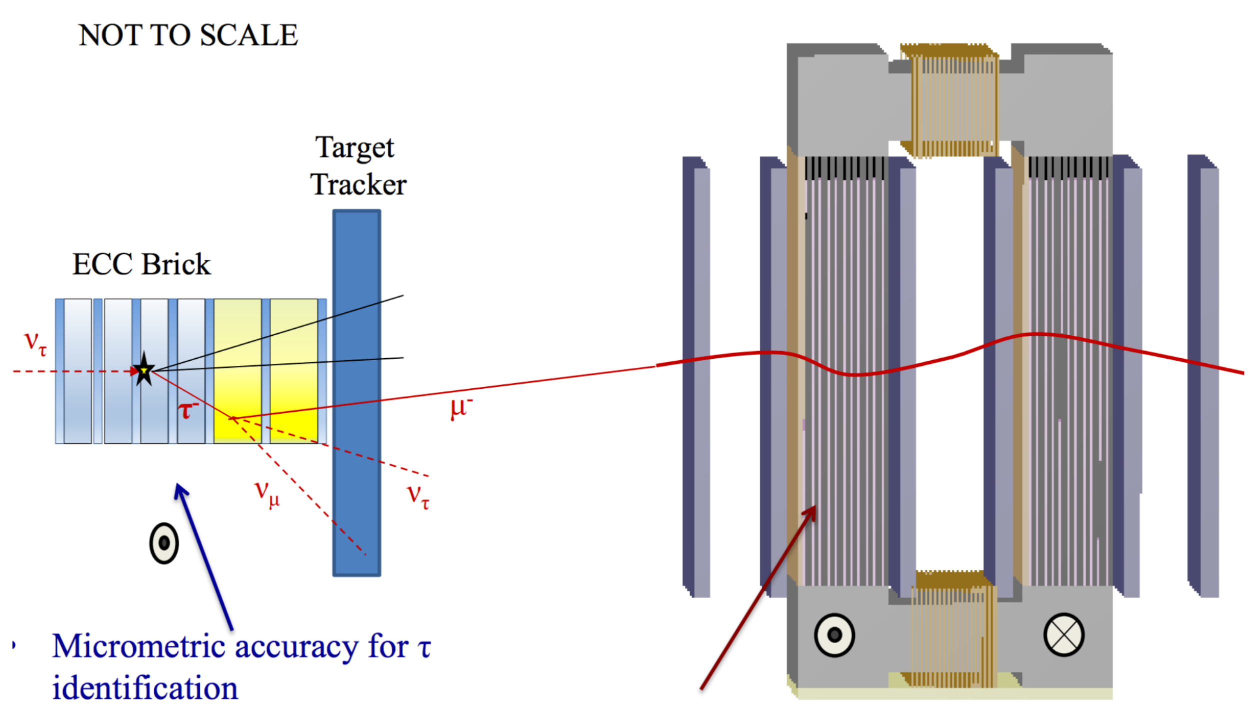


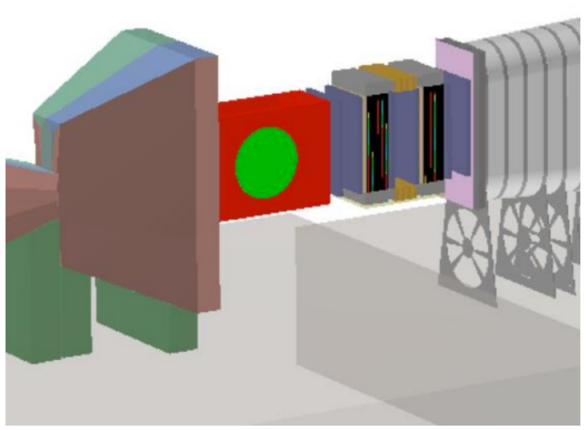


τ→K decays
slightly low...



Can an O(3-4k) ν_τ sample at SHiP impact a scenario like this?





(see talk by N. Serra)

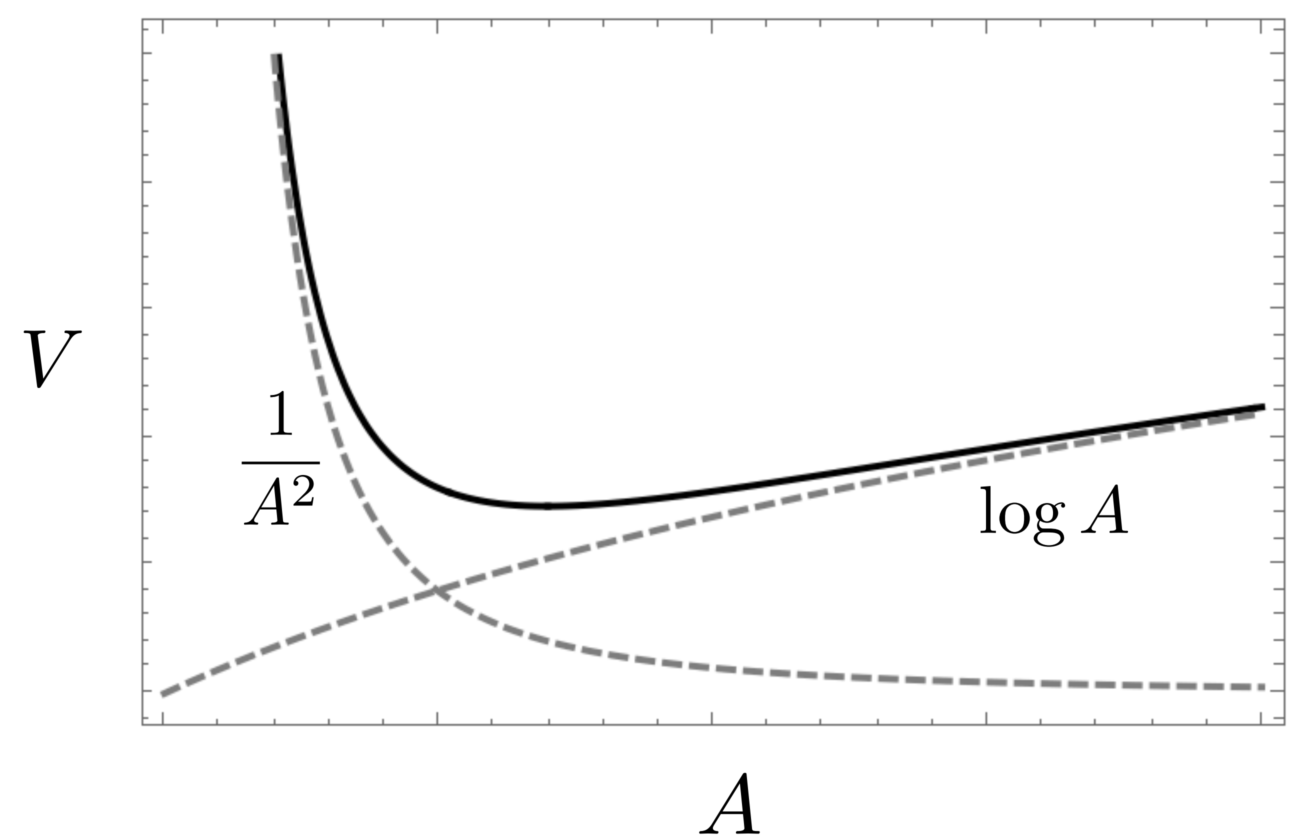
Sterile neutrino portal to a light scalar

Consider $\mathcal{L}_{\rm mass} = -m_D \nu N - m_N N N + \text{h.c.}$

with $m_N(A) = m_0 + \kappa A$ $\qquad V_0 = \Lambda^4 \log\left(1 + \left|\frac{A}{\sigma}\right|\right)$

$$V(A,T) = \Lambda^4 \log\left(1 + \left|\frac{A}{\sigma}\right|\right) + \frac{m^2(A)\,T^2}{24} \qquad m \propto \frac{1}{A}$$

Temperature-dependent potential



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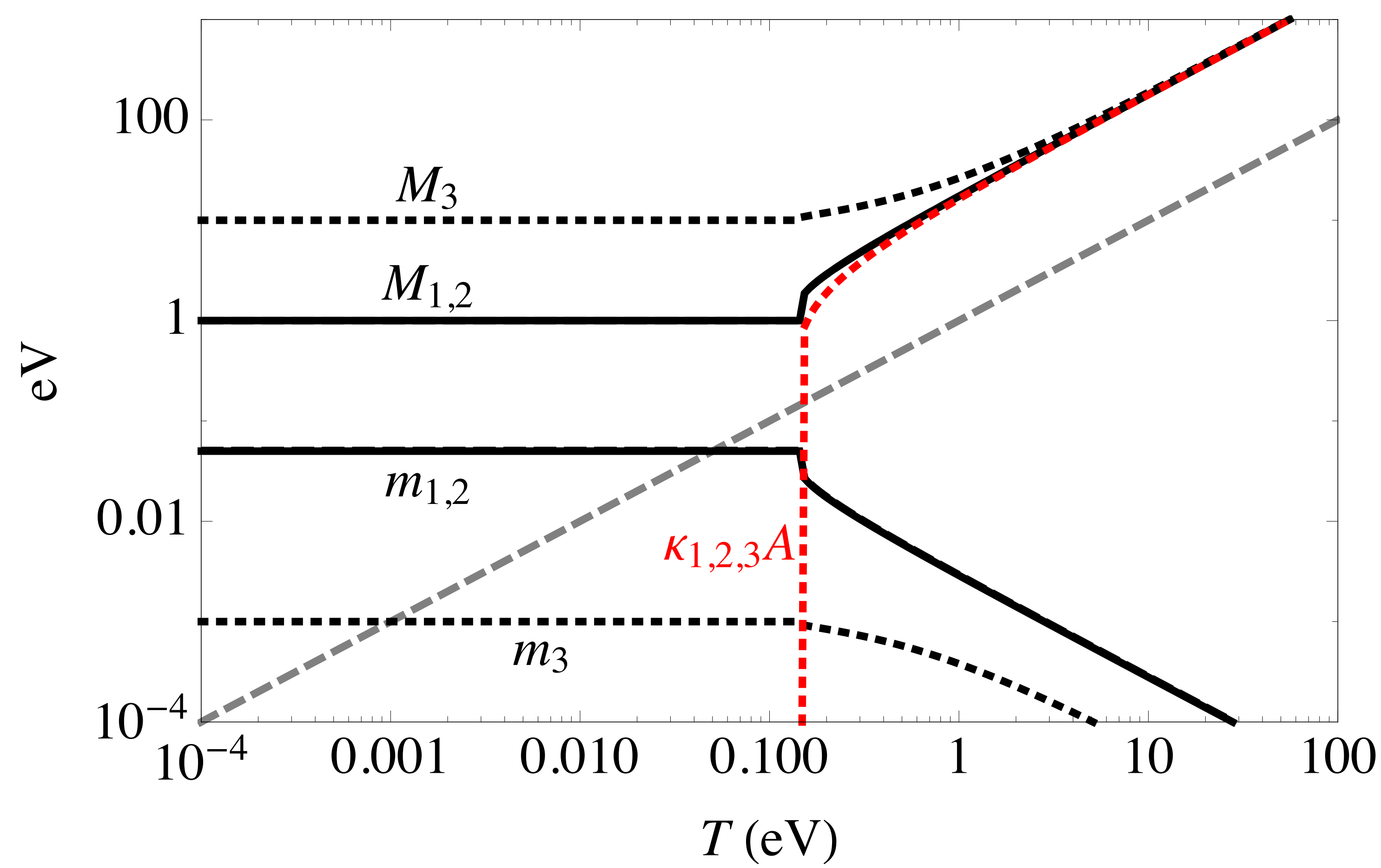

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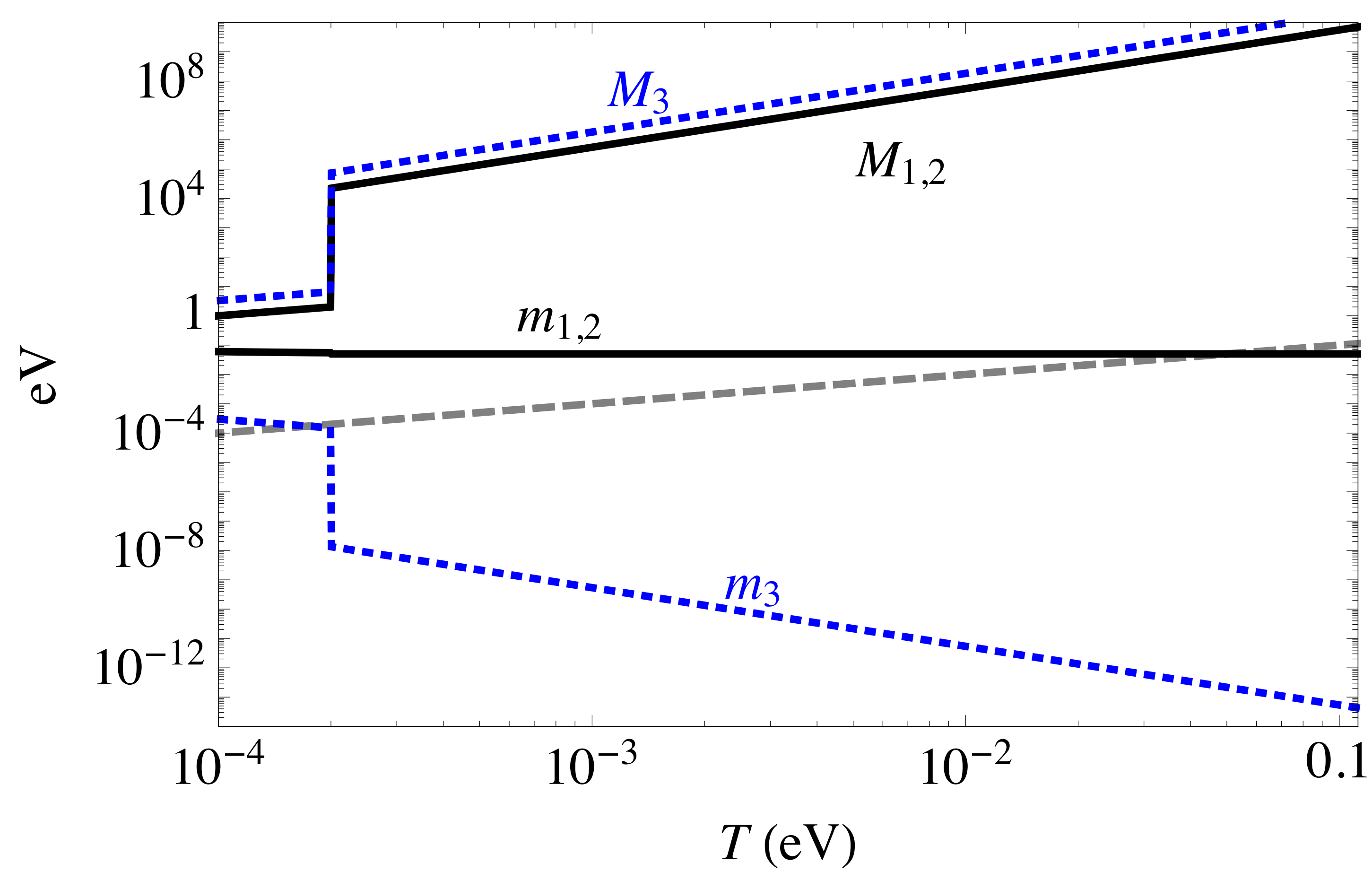
Add small active Majorana mass for dark energy

$\mathcal{L} \supset -\mu\nu\nu$



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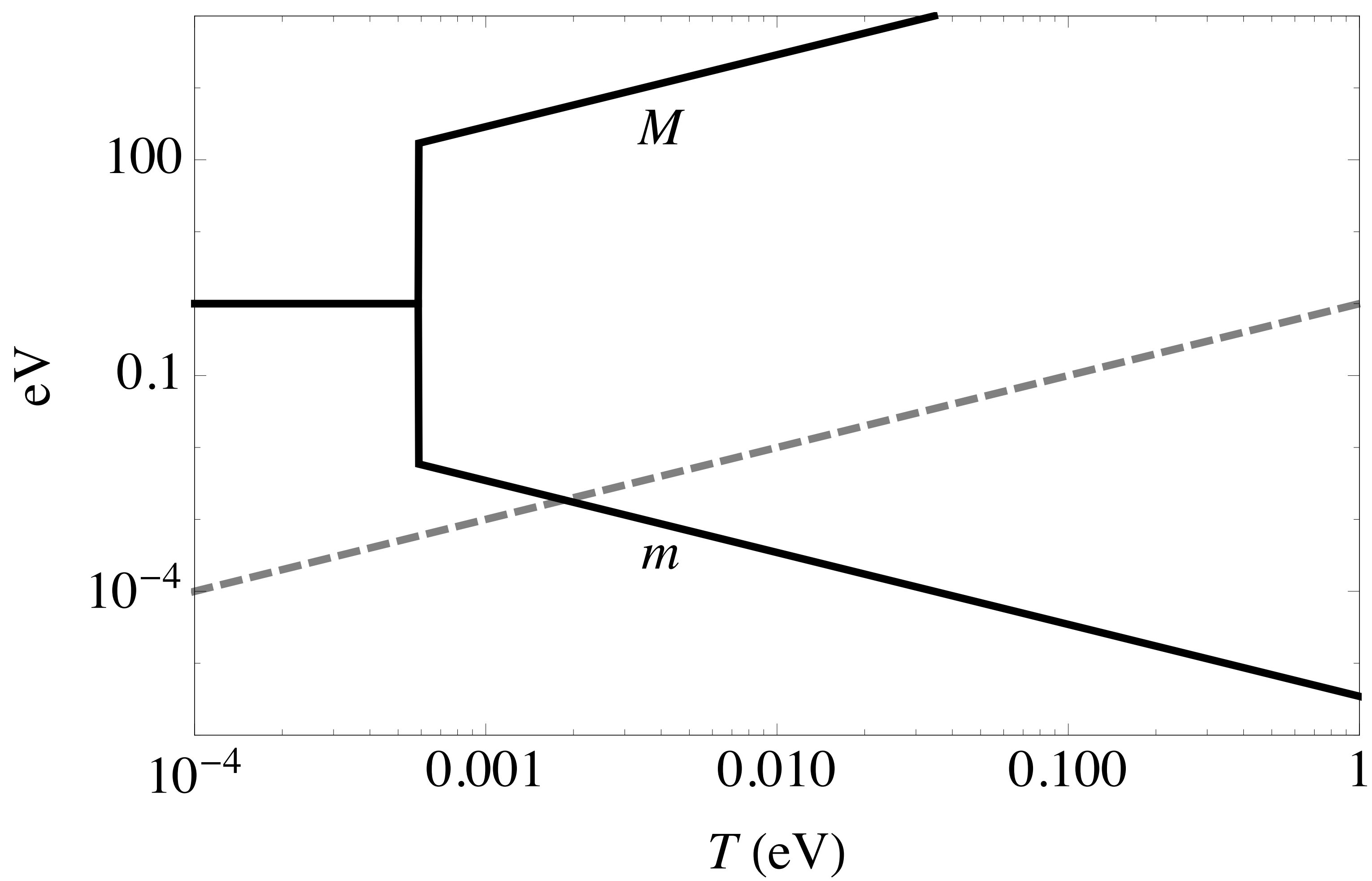
$$V(A,T) = \Lambda^4 \log\left(1 + \left|\frac{A}{\sigma}\right|\right) + \frac{m^2(A)\,T^2}{24}$$

Or get active neutrinos at an eV

~massless till late times, then "nuggets" form



Wrap up

Neutrino portal is a viable, less well studied way to couple to dark sector

Leads to a rich phenomenology

Can help with some problems in dark matter

Interesting new probes—lots of connections across fields!