The Flavour of Cosmology

David McKeen

TRIUMF

FPCP @ University of Victoria

May 7, 2019

*title borrowed from Lillard, Ratz, Tait, & Trojanowski

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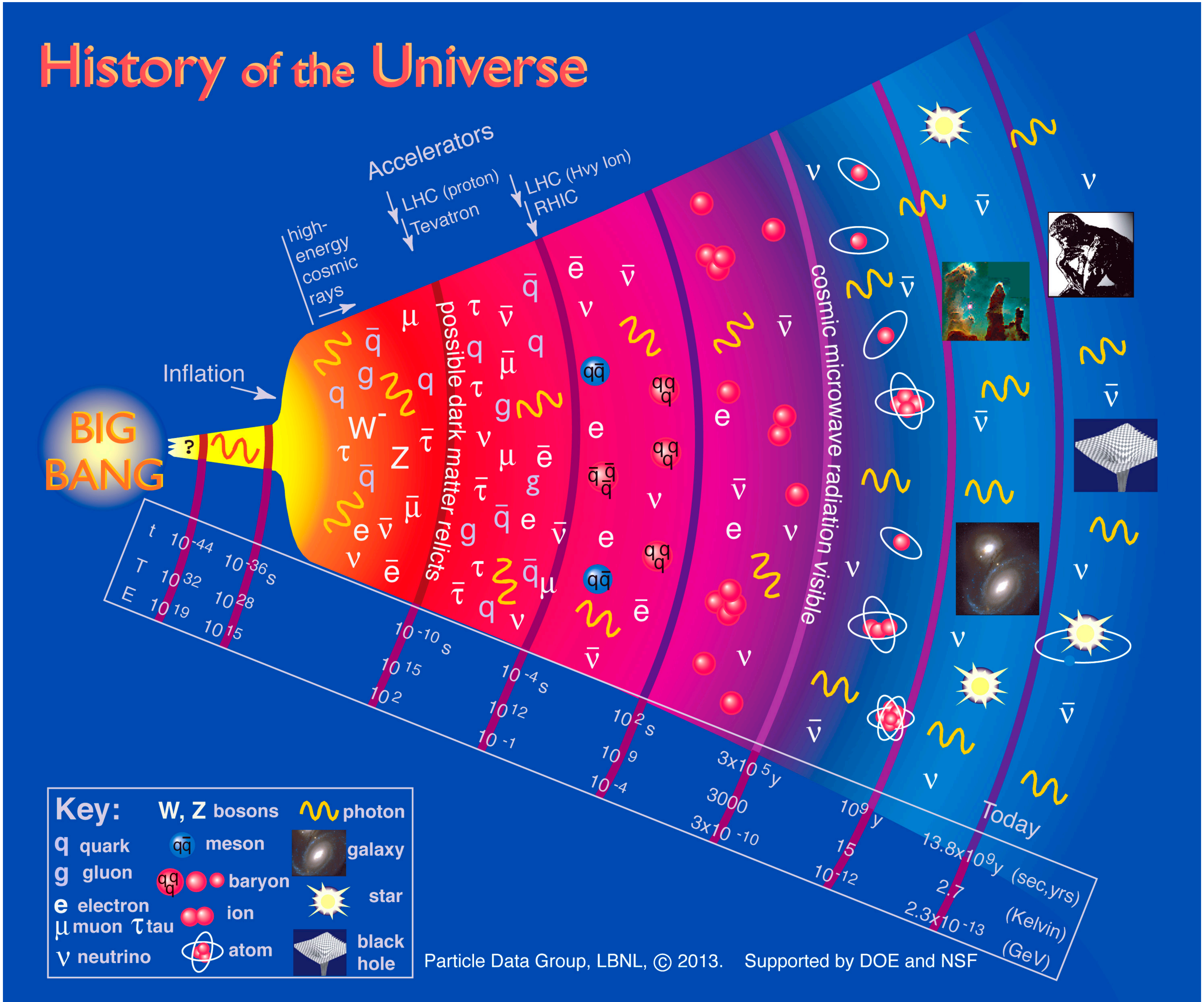
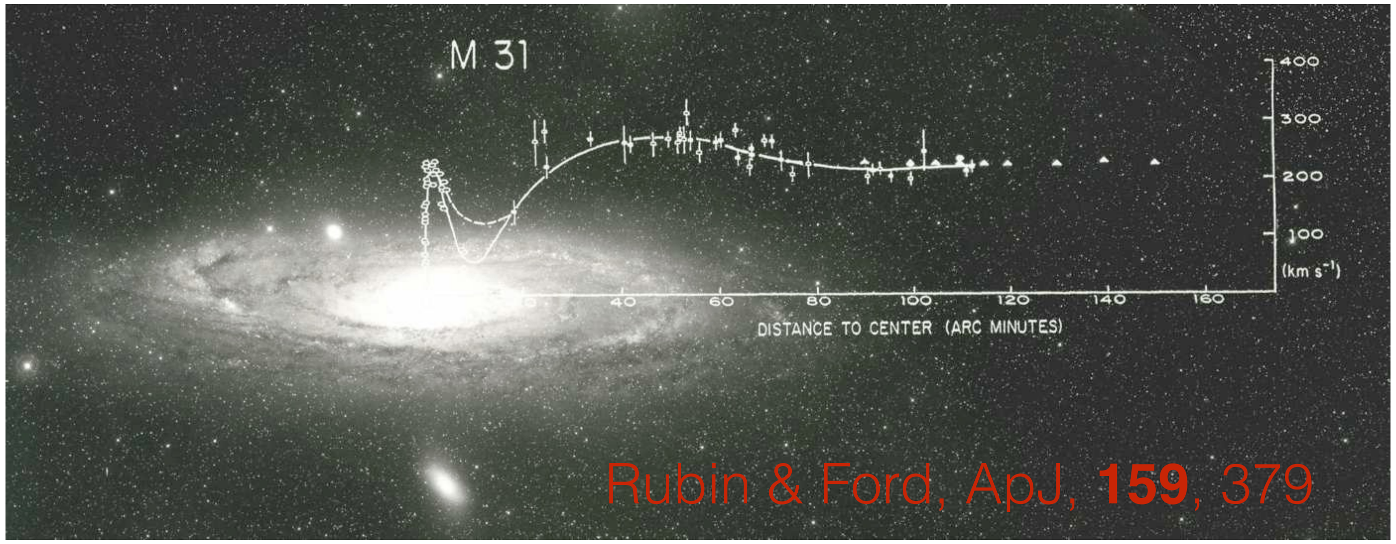
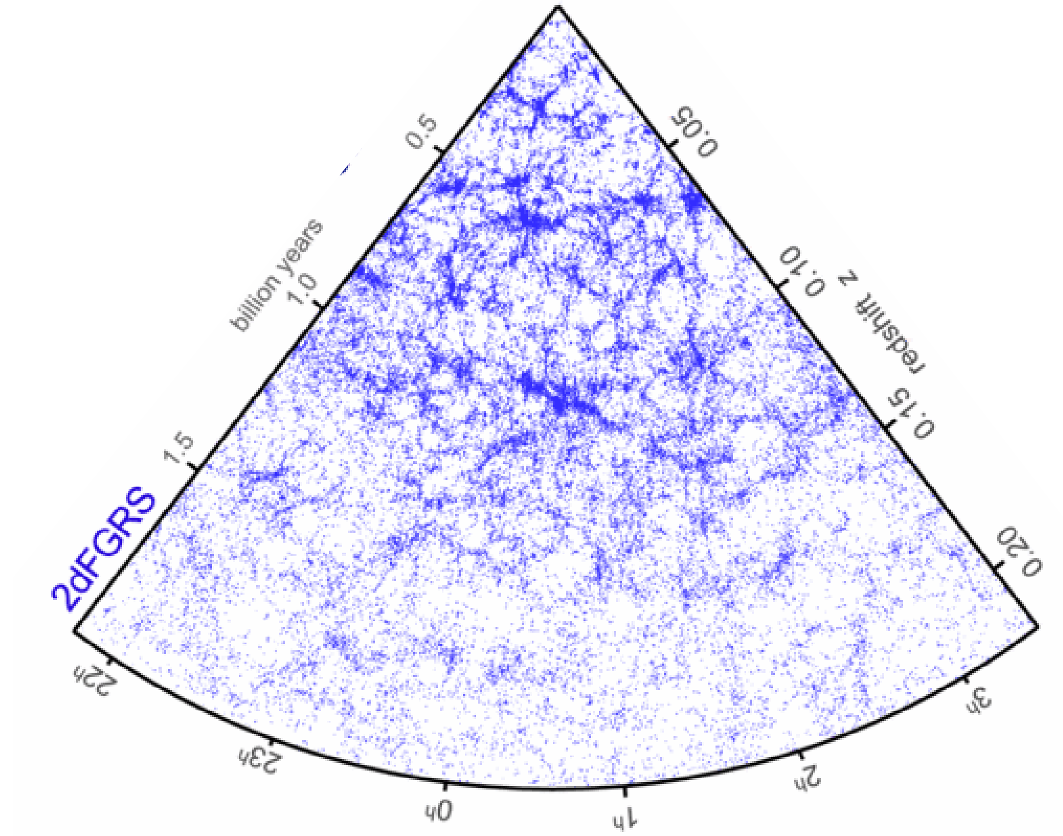
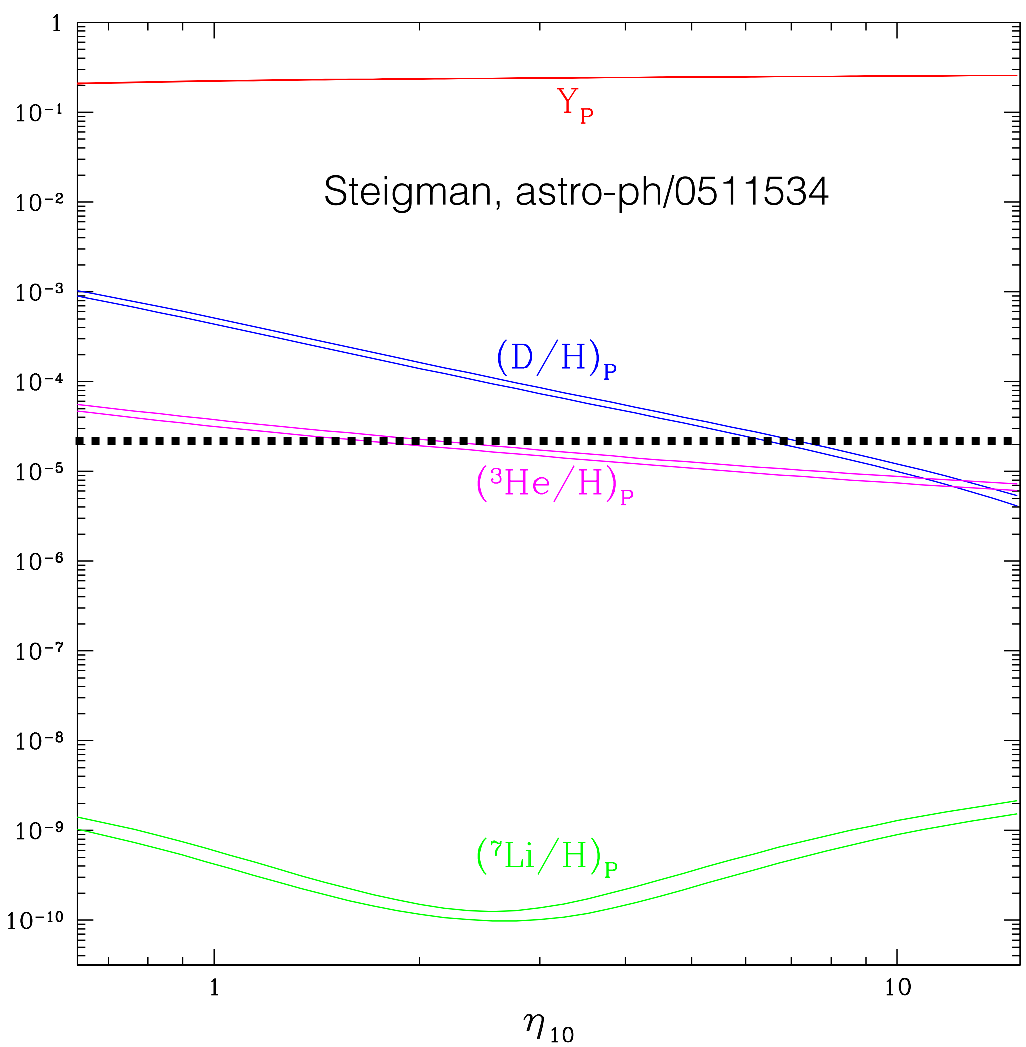
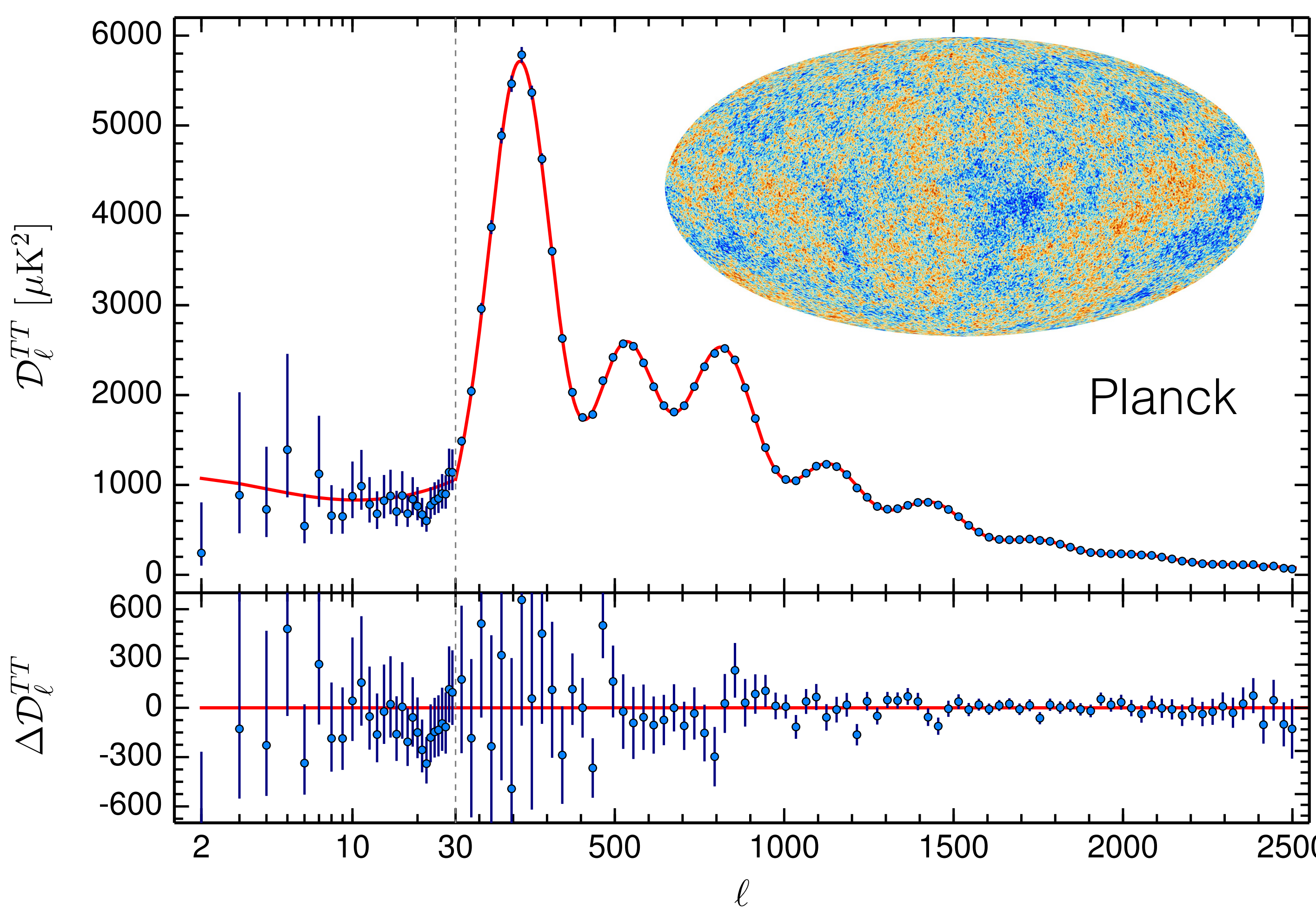

History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC (proton)
Tevatron
LHC (Hvy Ion)
RHIC
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-36 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-4 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
13.8x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2013. Supported by DOE and NSF

Lots of data

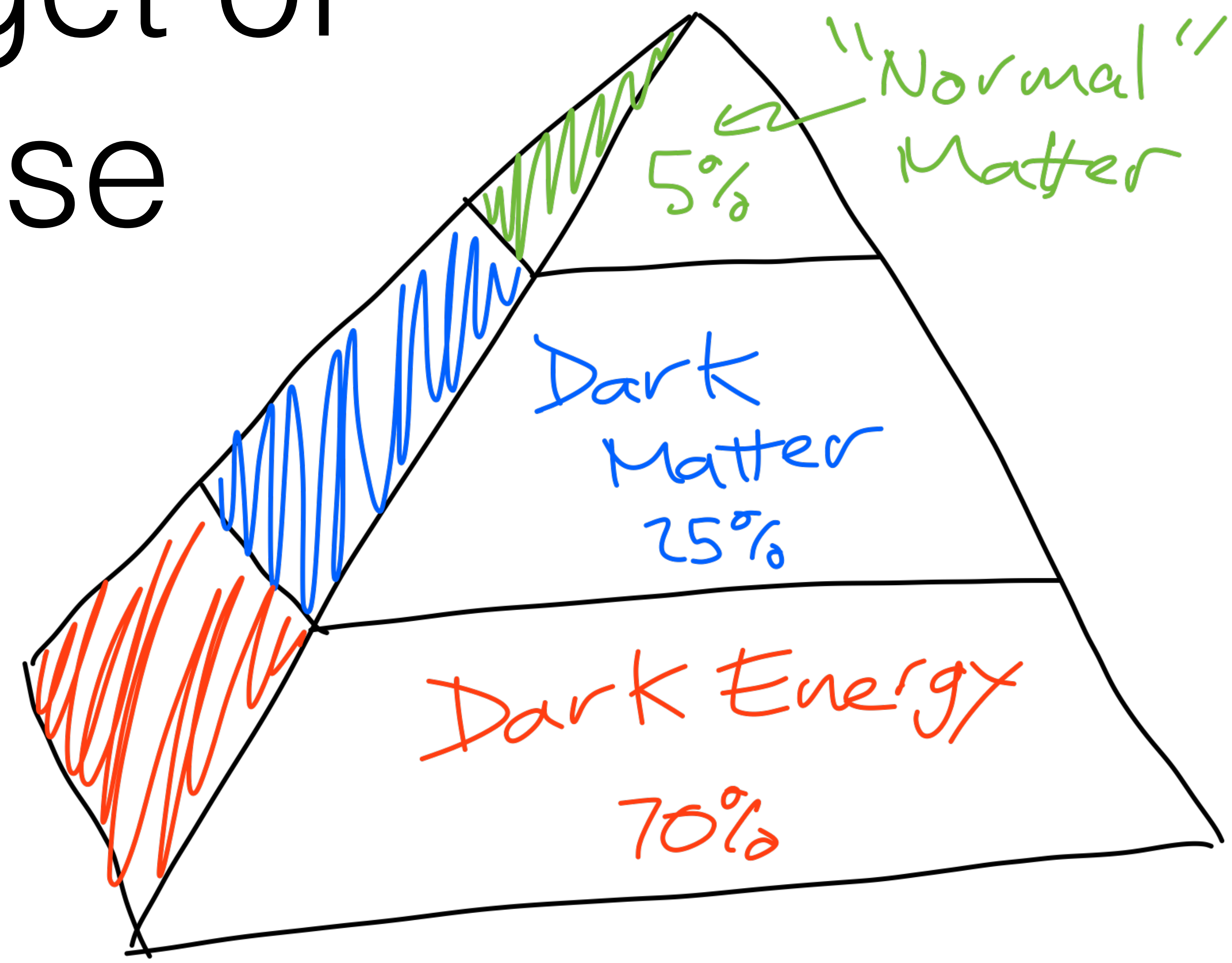

M 31
DISTANCE TO CENTER (ARC MINUTES)
(km s⁻¹)
Rubin & Ford, ApJ, **159**, 379


2dFGRS
billion years
redshift z

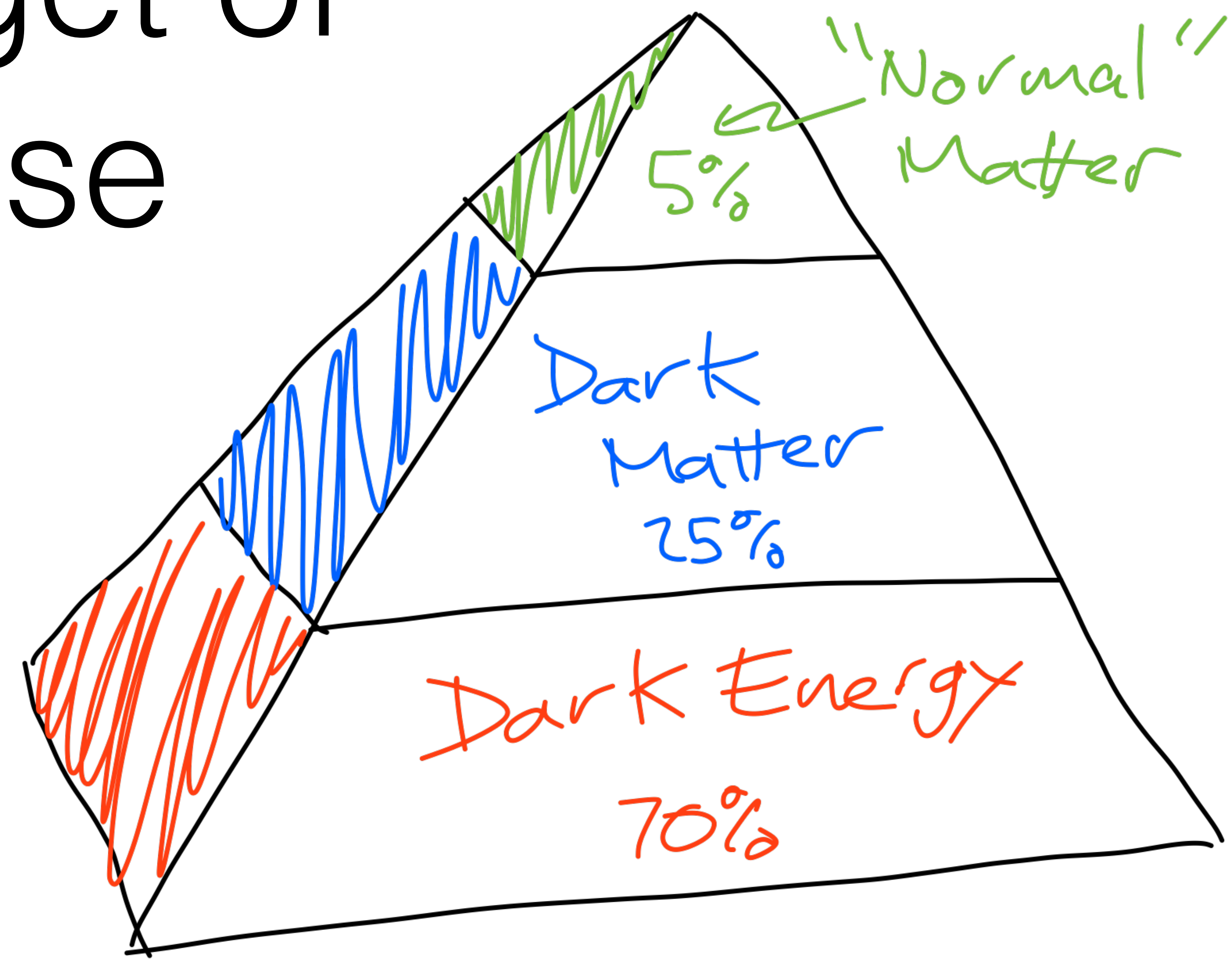

Steigman, astro-ph/0511534
Y_P
$(D/H)_P$
$(^3He/H)_P$
$(^7Li/H)_P$
η_{10}


Planck
$\mathcal{D}_\ell^{TT}\ [\mu K^2]$
$\Delta\mathcal{D}_\ell^{TT}$
ℓ

Energy Budget of the Universe

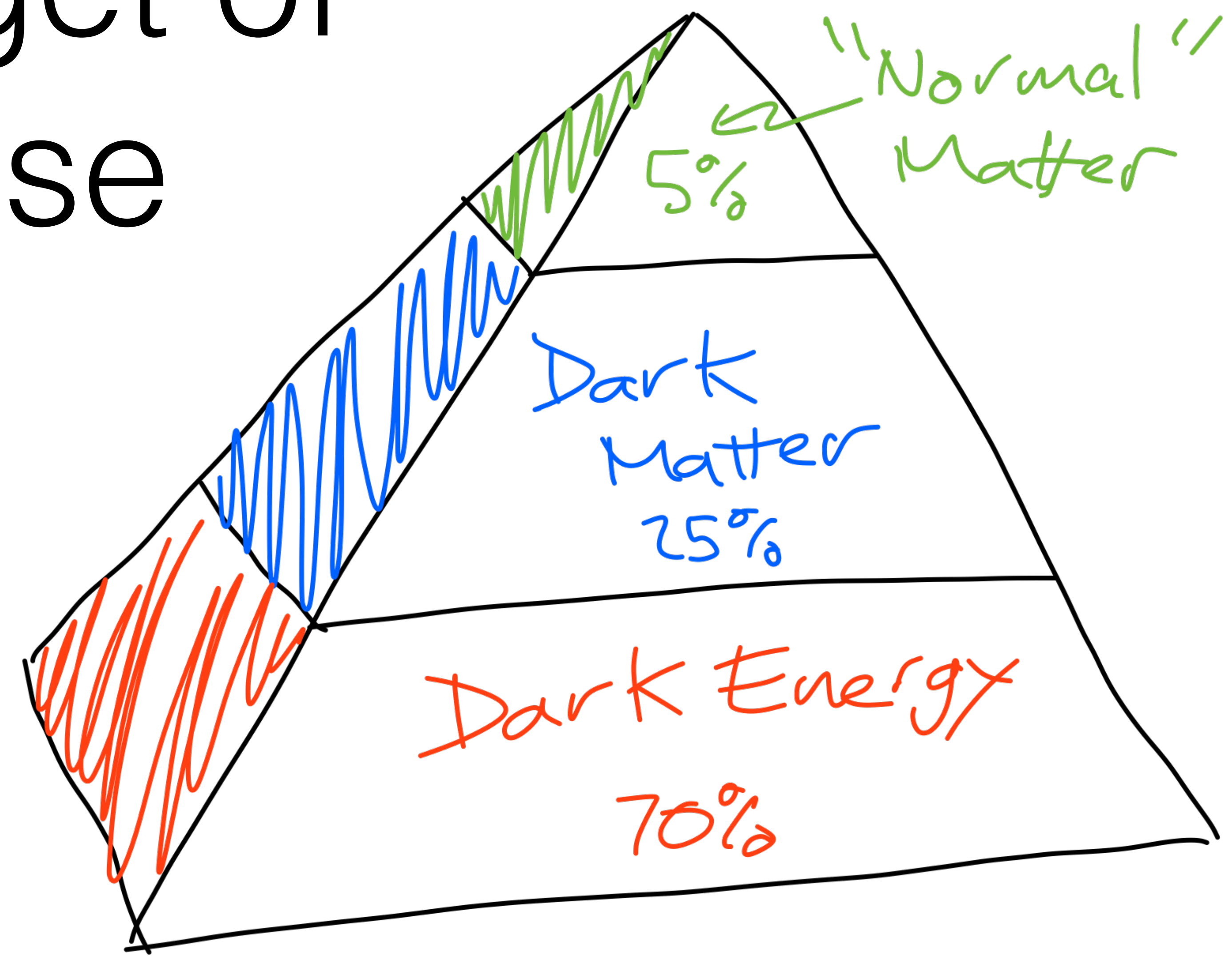


Energy Budget of the Universe



What can flavour say about this?

Energy Budget of the Universe



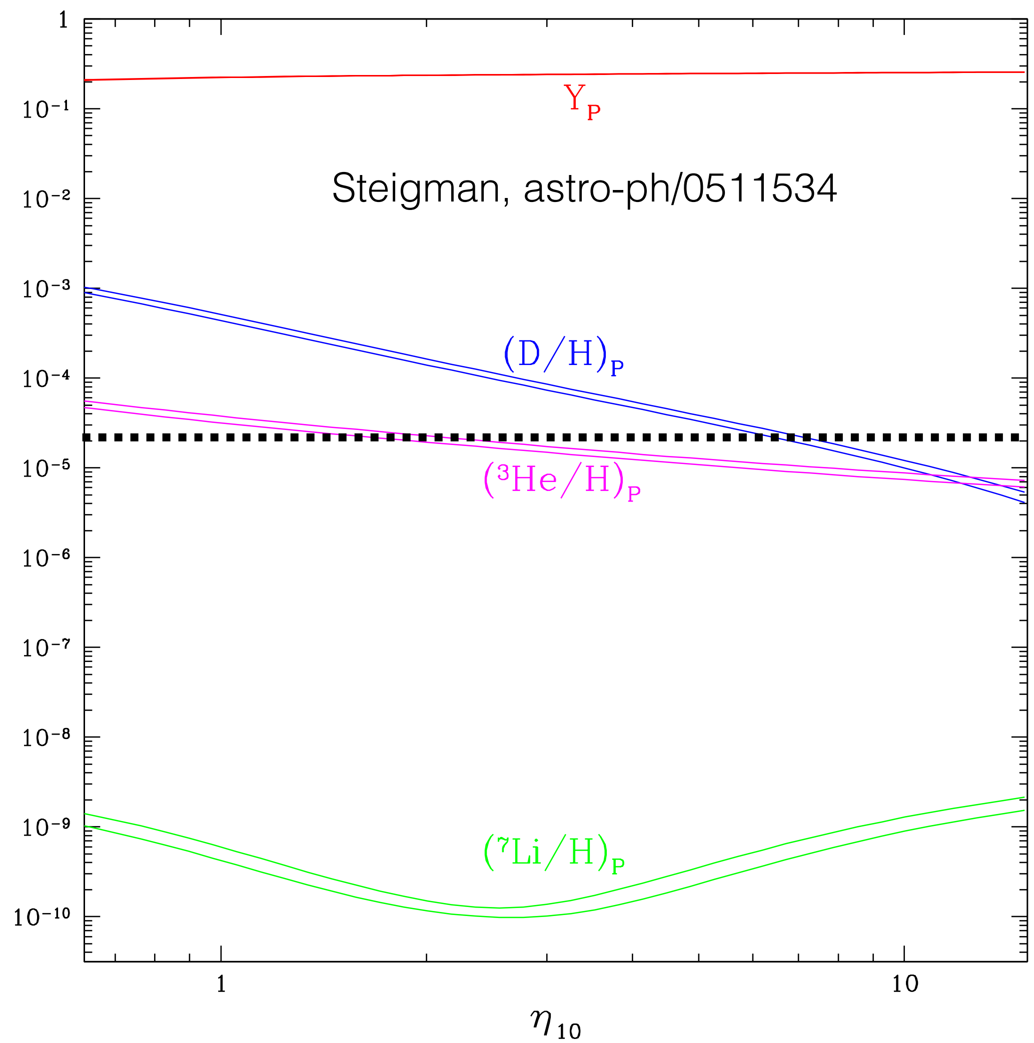
What can flavour say about this?

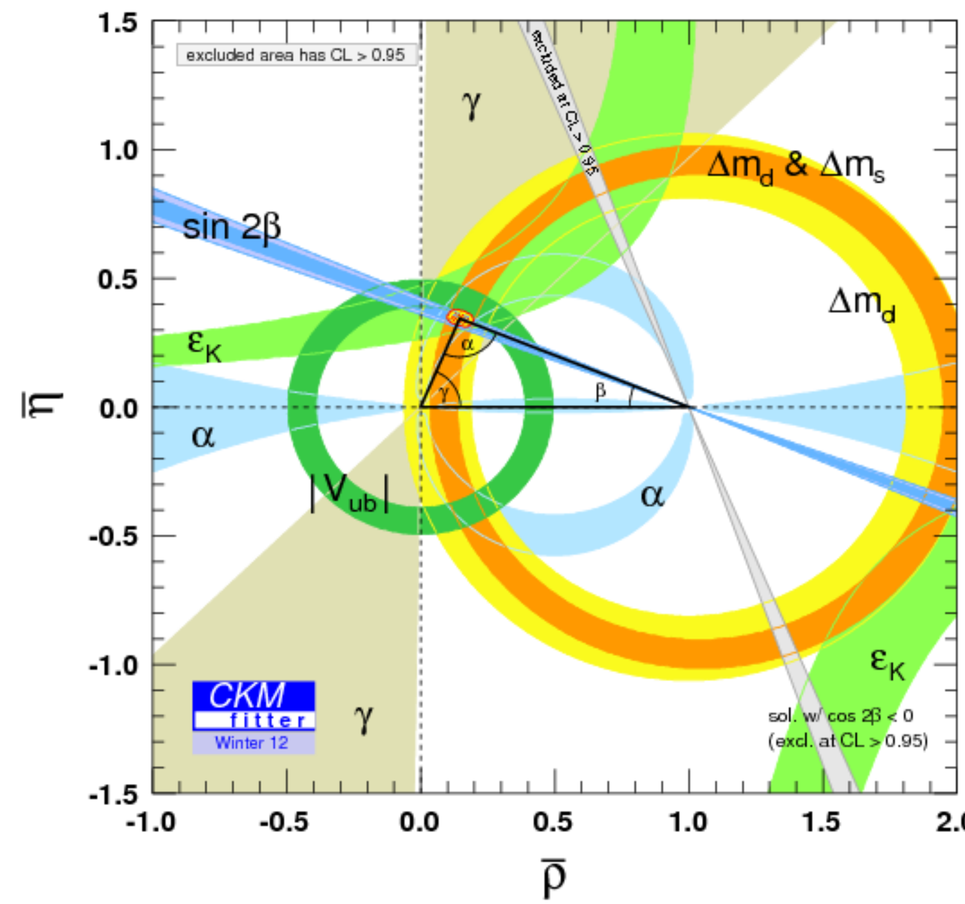
(the people here)

First, the “normal” matter

More baryons than antibaryons

Sakharov conditions:
B violation (SM: ☑)
C & CP violation (SM: “☑”)
Leave thermal eq. (SM: ☒)



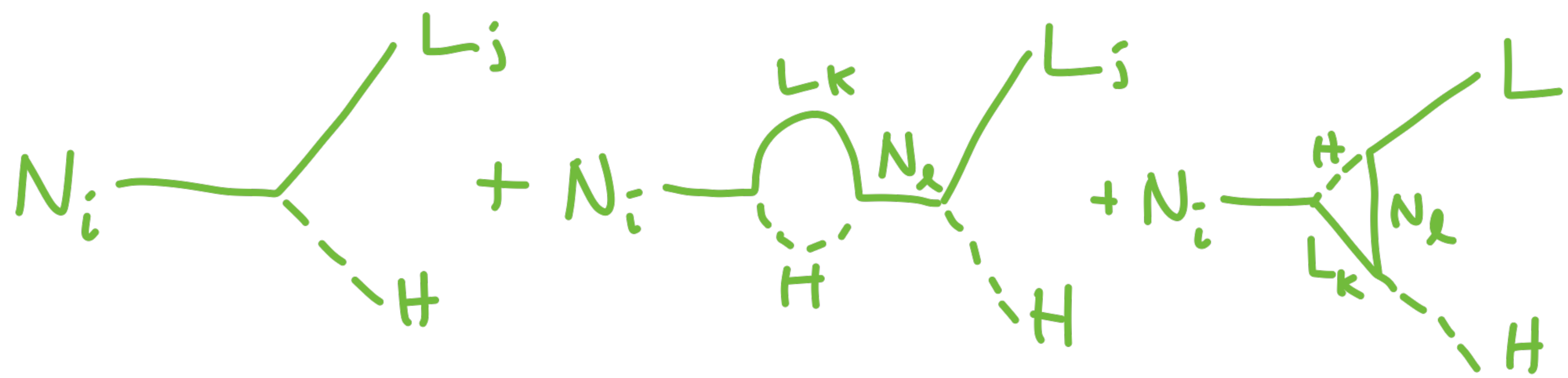


SM can't quite do it

Fukugita & Yanagida

Vanilla Leptogenesis

Heavy ($\gtrsim 10^9$ GeV) sterile neutrinos decay out-of-eq.



Create lepton asymmetry ⇒ baryon asymmetry by SM sphalerons (violate B+L, conserve B-L)

However: hard to directly test & high reheat temperature problematic

Akhmedov, Rubakov & Smirnov; Asaka & Shaposhnikov

Resonant Leptogenesis

Light (~ GeV) sterile neutrino oscillations $N_i \leftrightarrow N_j$

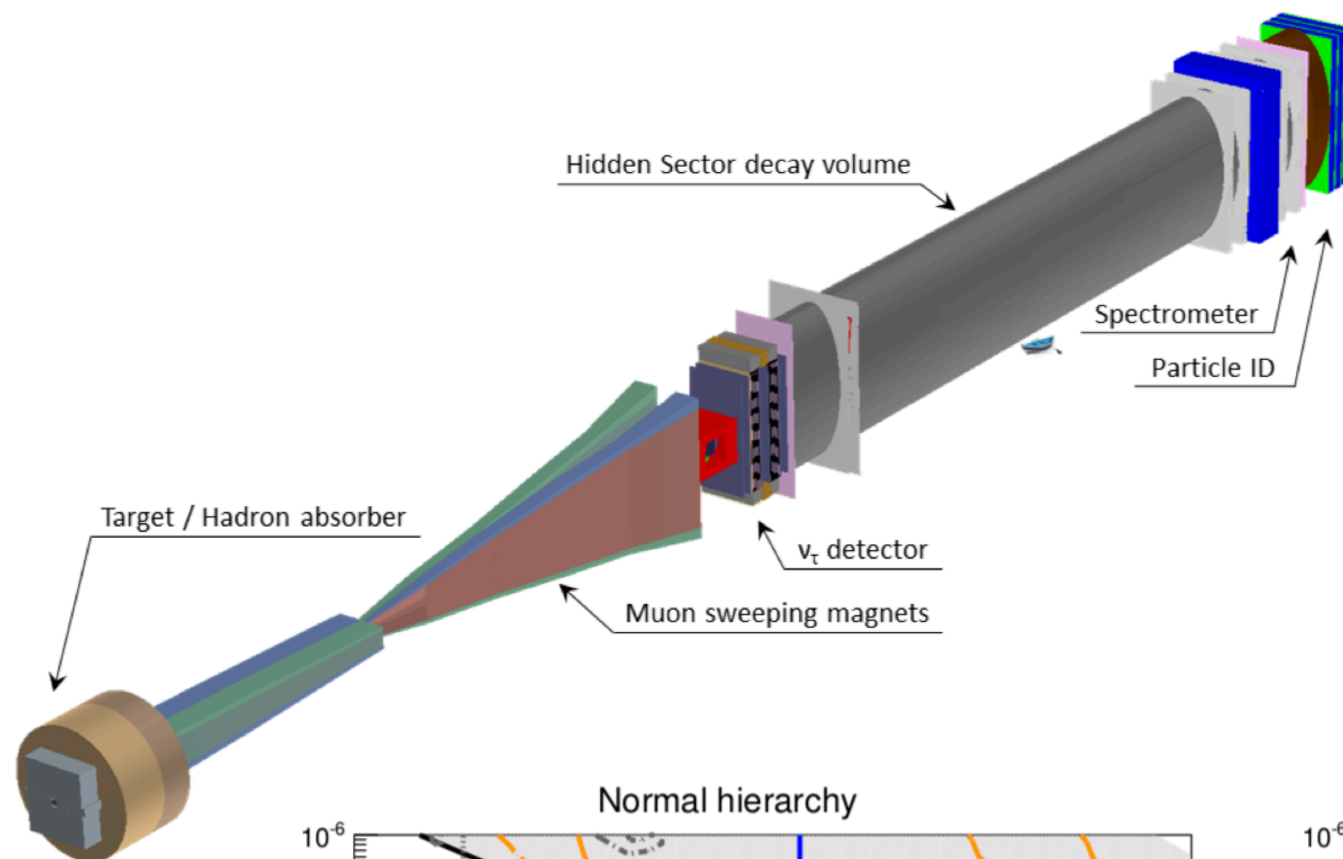
Small couplings so lepton number approximately conserved but individual lepton numbers not

$$\sum (n_i - \bar{n}_i) = 0, \quad n_j - \bar{n}_j \neq 0$$

One flavor in equilibrium, one not $\Rightarrow$ SM sphalerons transfer that into baryon asymmetry

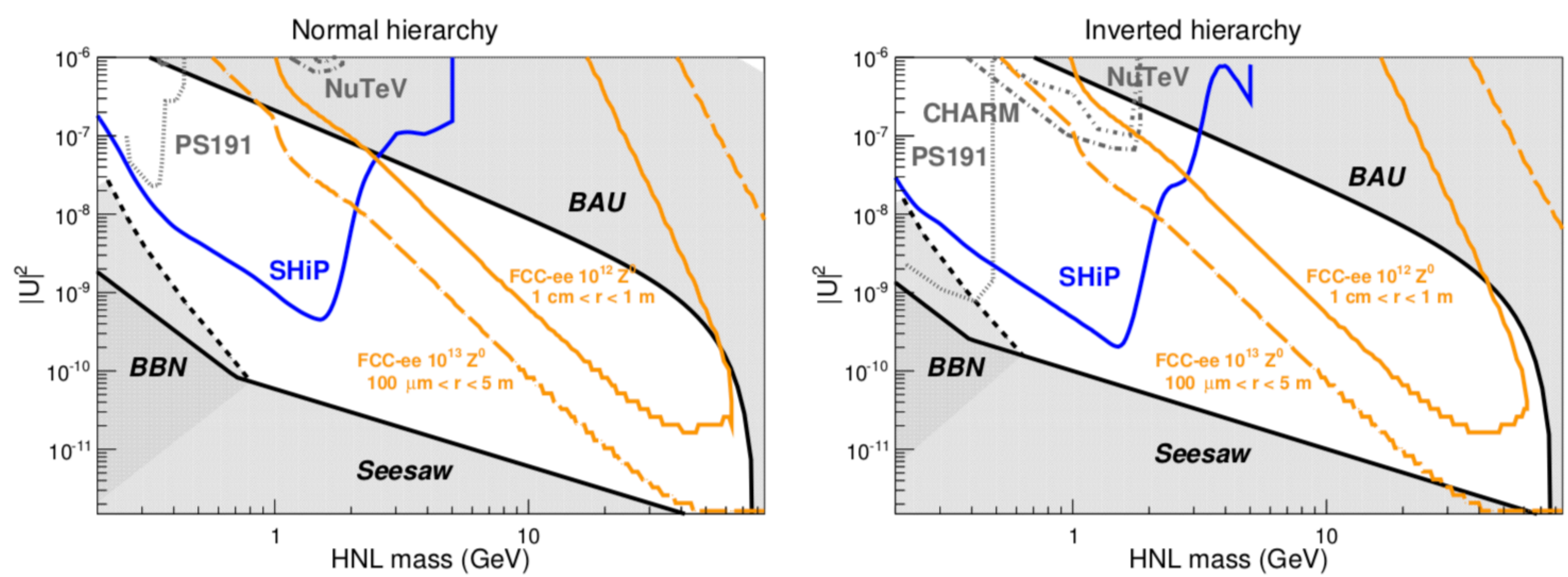
Out-of-equilibrium sterile neutrino decays after sphalerons turn off, does not cancel baryon asymmetry

Resonant Leptogenesis Tests



SHiP Experiment

400 GeV protons



Any other mechanisms?

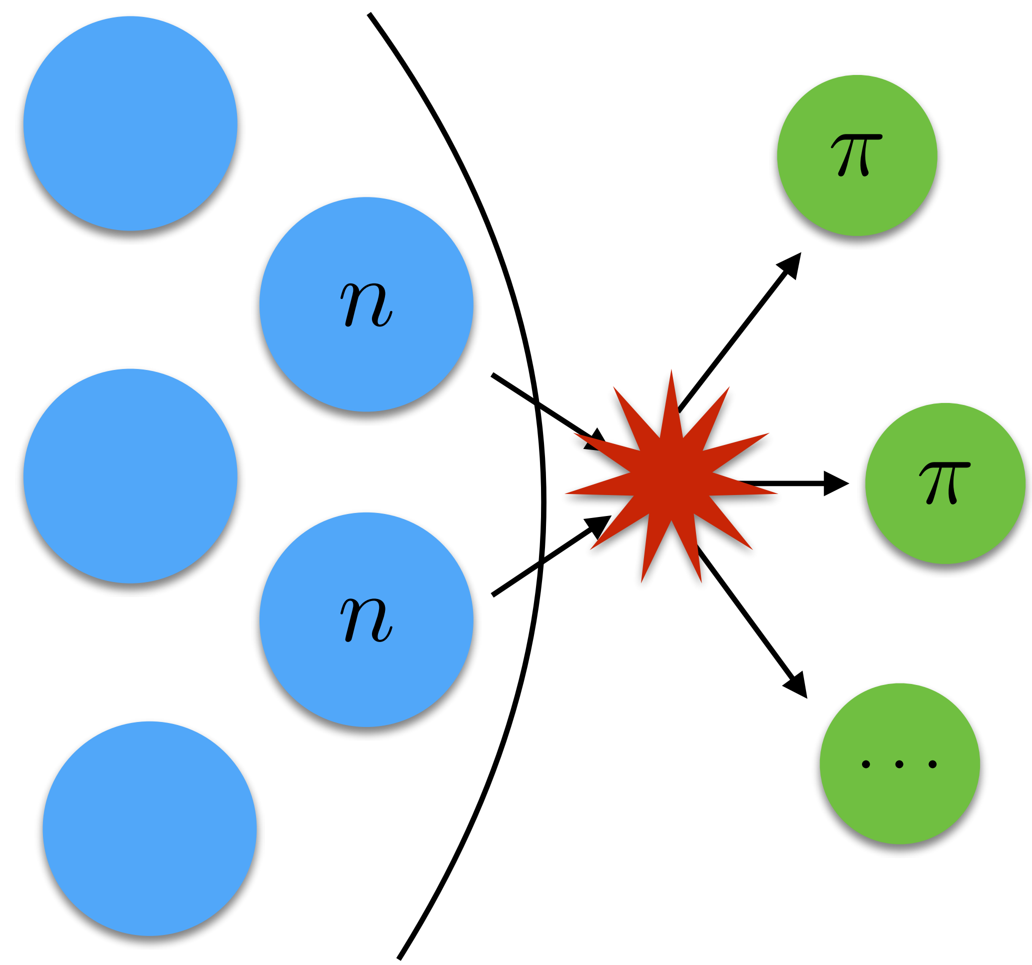
Baryon-antibaryon oscillations

Proton decay is very constraining on ΔB=1 models.
What if ΔB=2 instead?

Present best limit comes from Super-K limit on lifetime of ^{16}O: $\tau_{^{16}\mathrm{O}} > 1.9 \times 10^{32}\ \mathrm{yr}$

(translates to $\tau_{n\to\bar{n}} > 3.5 \times 10^{8}\ \mathrm{s}$
or $\left| M_{12} - \frac{i}{2}\Gamma_{12} \right| < 1.9 \times 10^{-33}\ \mathrm{GeV}$)

$$\left[\mathcal{L}_{\mathrm{eff}} \supset \frac{(udd)^2}{\Lambda^5} \Rightarrow M_{12}, \Gamma_{12} \propto \frac{1}{\Lambda^5},\ \Lambda \gtrsim 100\ \mathrm{TeV}\right]$$



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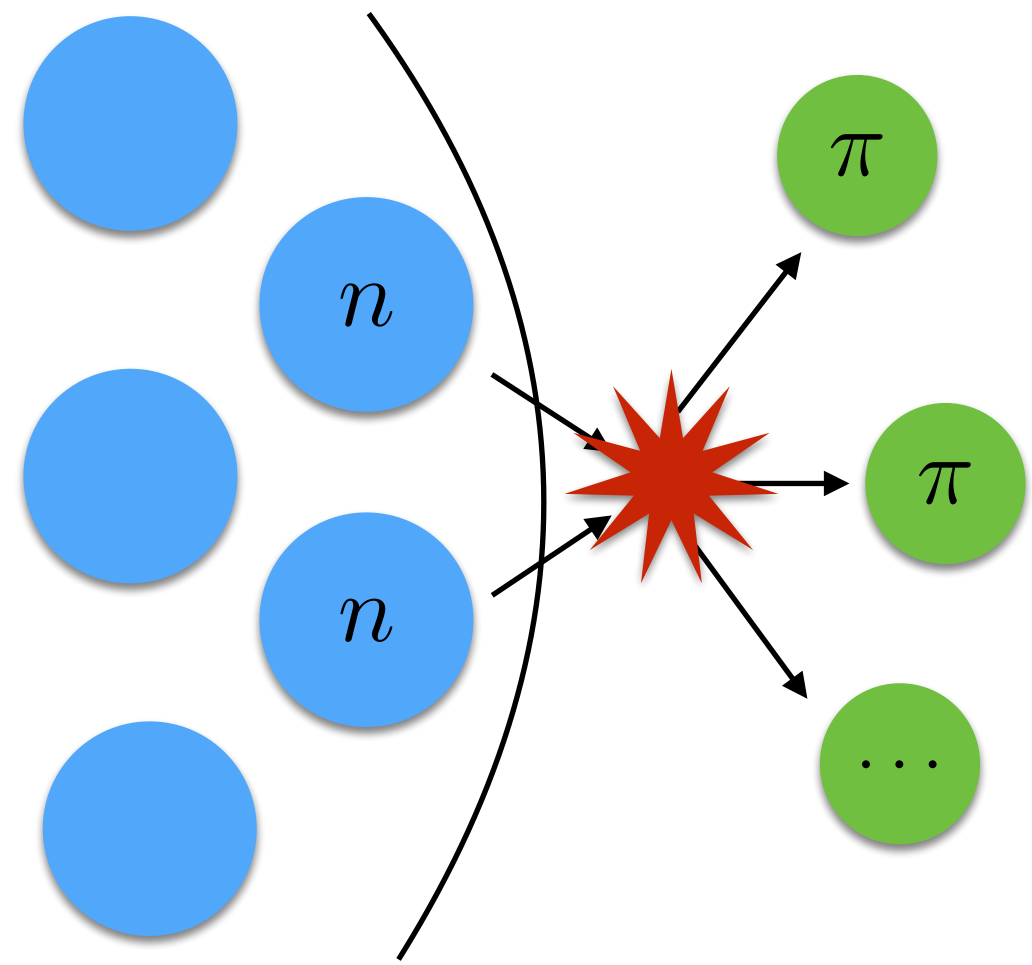


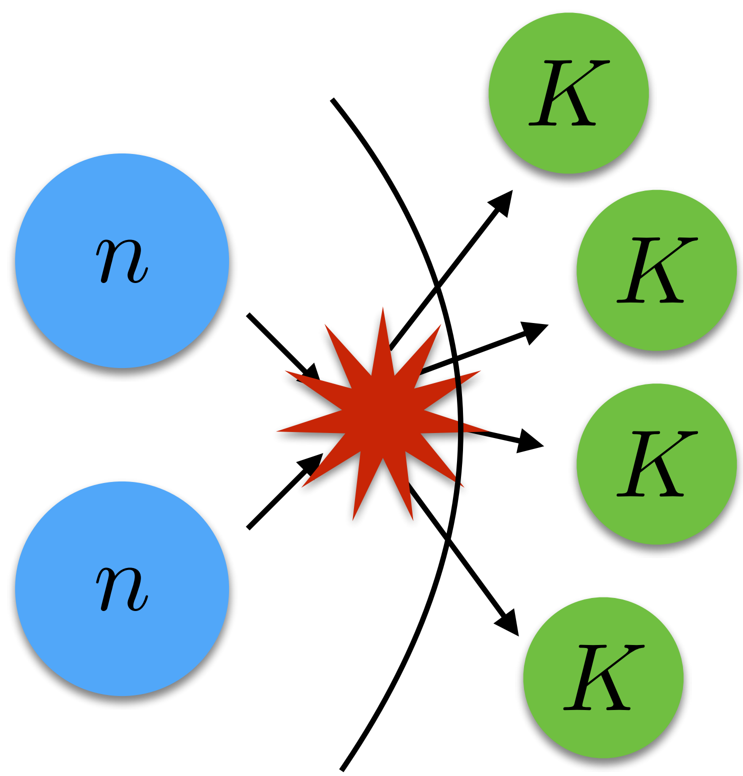
But…

DM & Nelson, PRD **94** 076002 [1512.05359]

Baryon-antibaryon oscillations

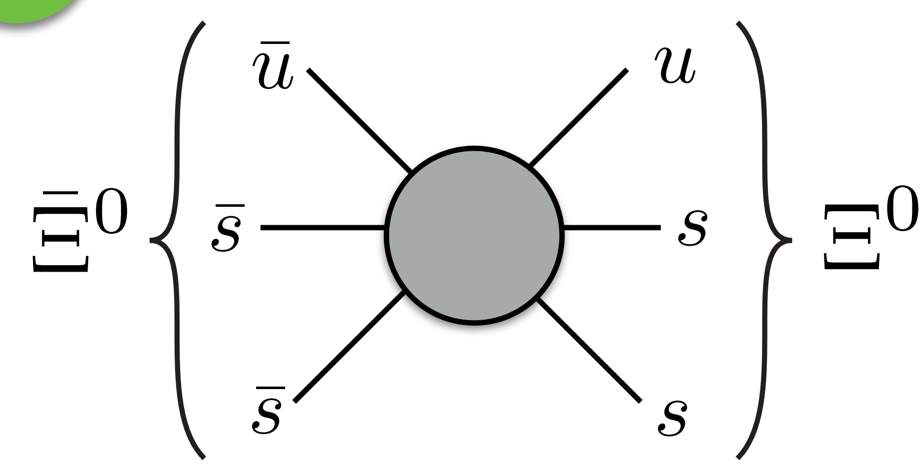
What if ΔB=2 operators had, e.g., ΔS=4? $\mathcal{L}_{\rm eff} \supset \frac{(uss)^2}{\Lambda^5}$

Then direct dinucleon decay



is kinematically forbidden!

Leads to oscillation of cascade baryons



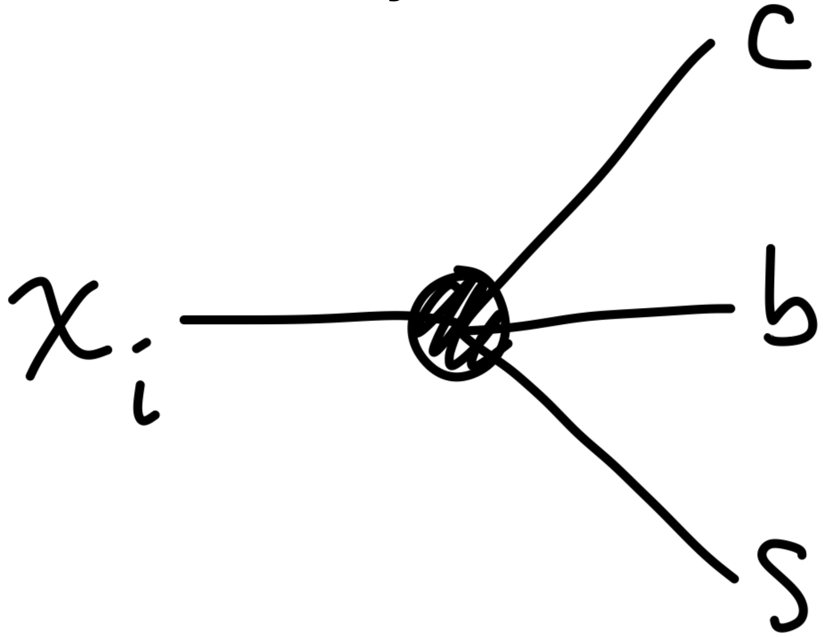
Dominant constraints could be from colliders

$\Gamma_{12},\ M_{12}$ could be much, much larger Kuzmin ('94)

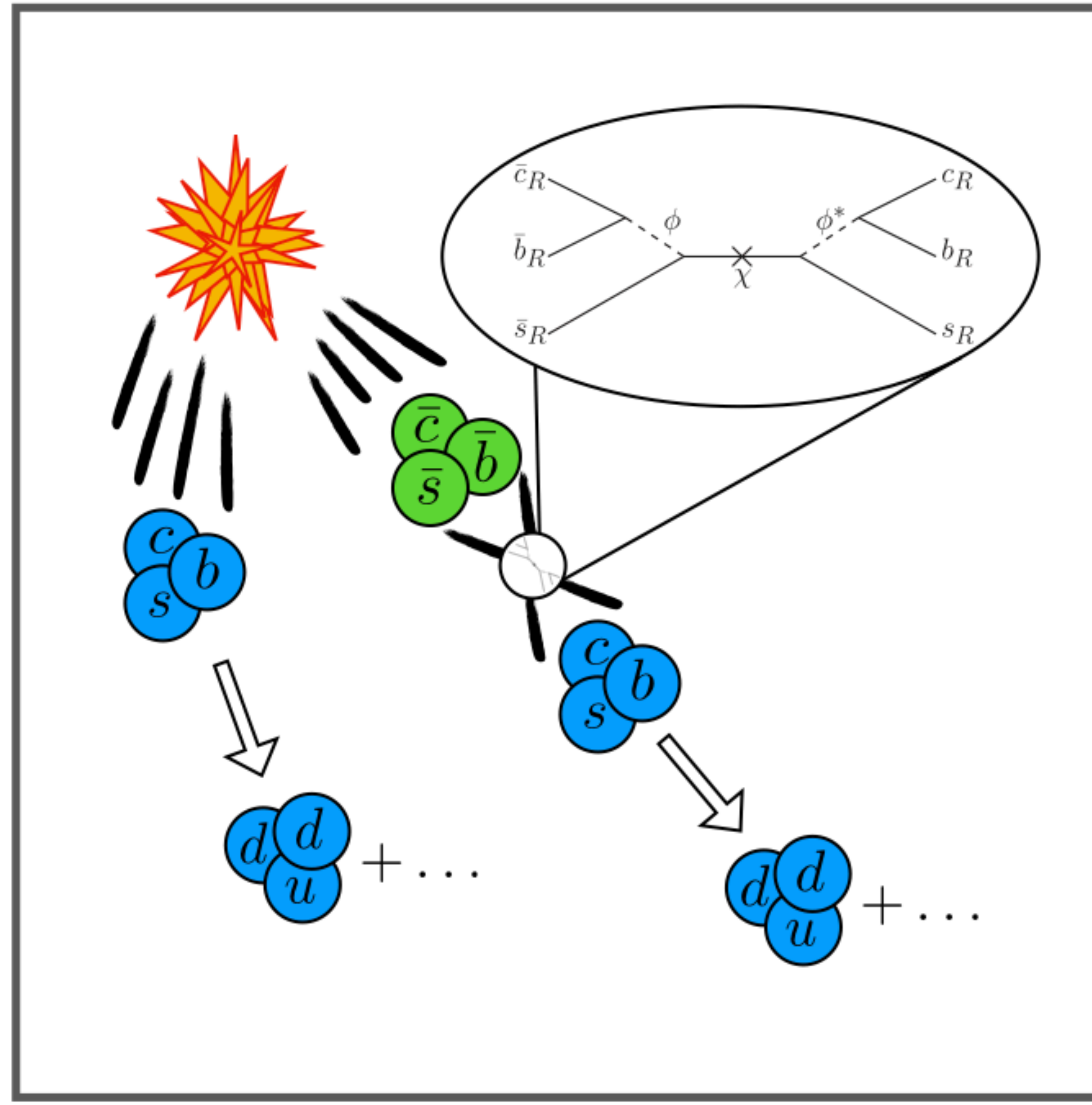
Aitken, DM, Neder, & Nelson, PRD **96** 075009 [1708.01259]

Baryon-antibaryon oscillations

Introduce Majorana fermions that couple to baryons



They mediate baryon-antibaryon oscillation & produce baryons out-of equilibrium



Aitken, DM, Neder, & Nelson, PRD **96** 075009 [1708.01259]

Baryon-antibaryon oscillations

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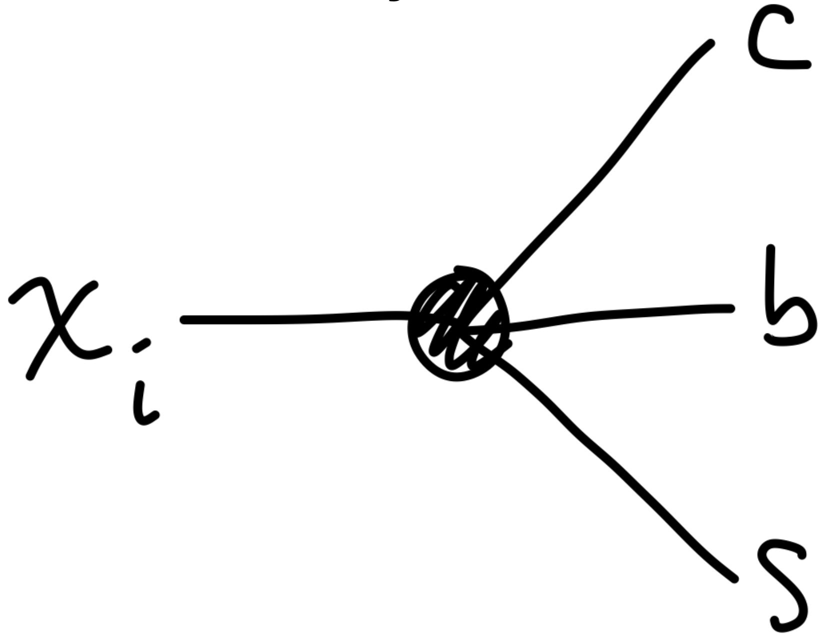

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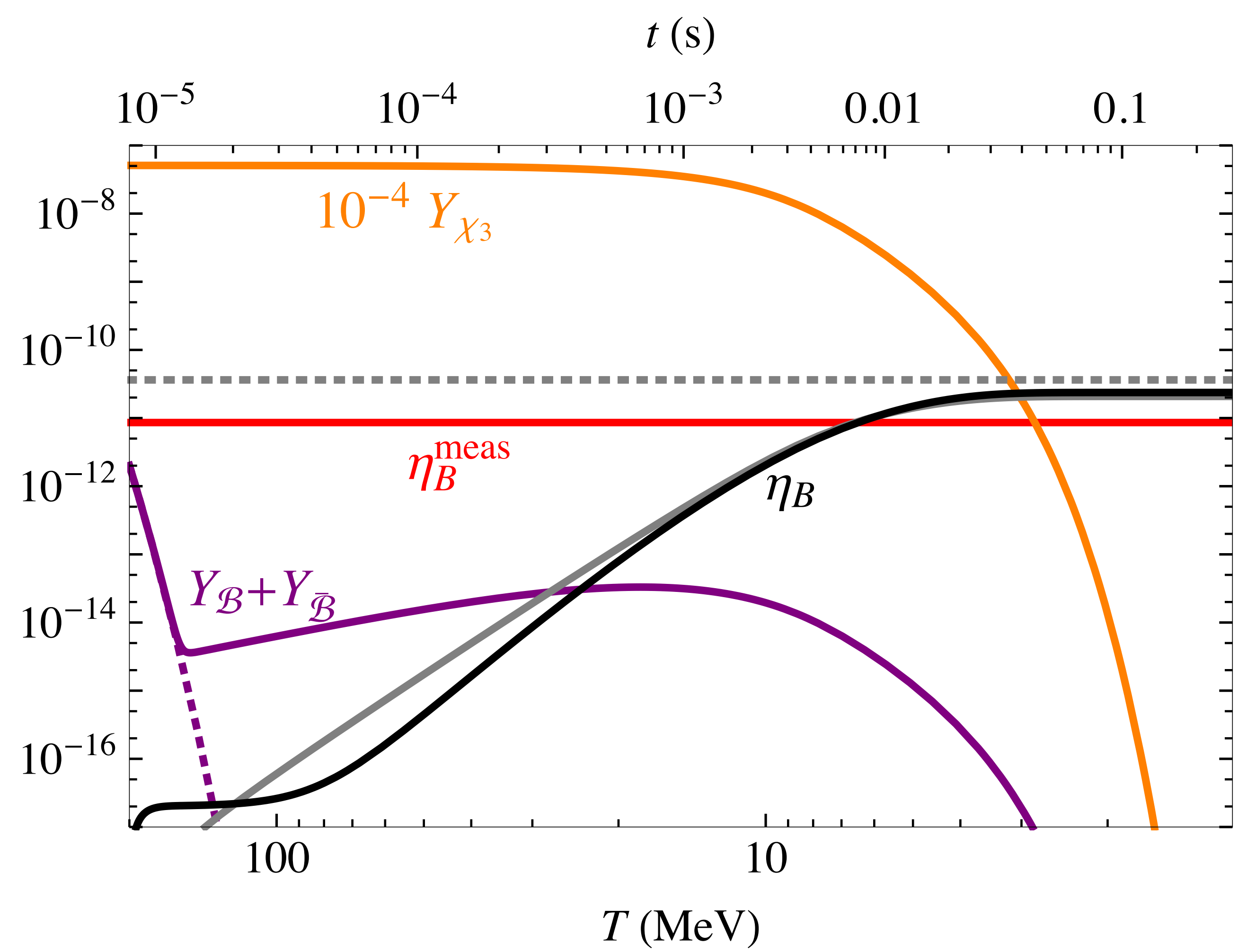
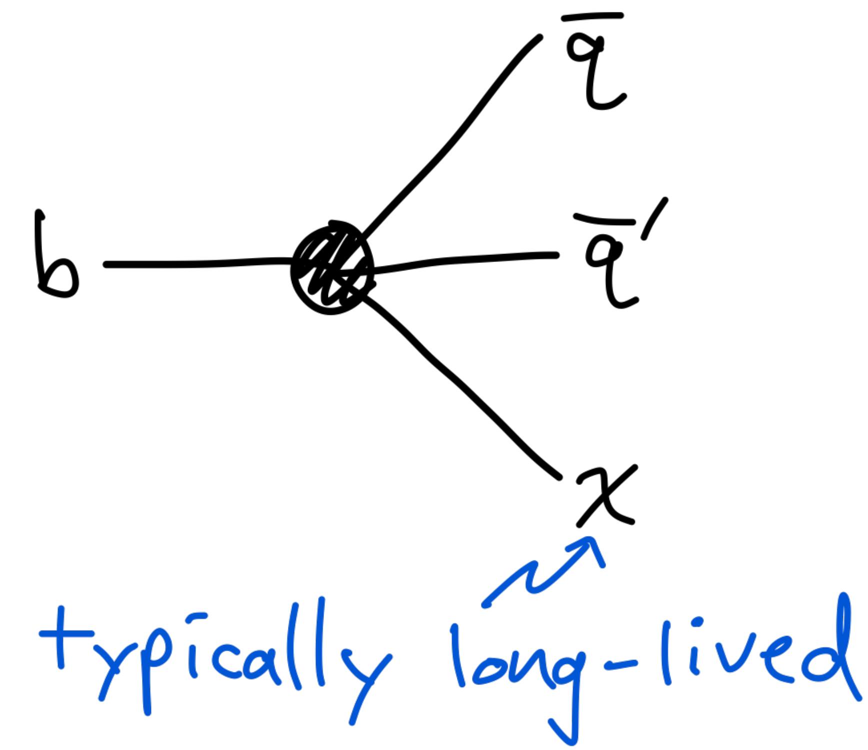


Testing this scenario

Related operators can mediate heavy quark decay



$$\text{meson} \to \text{baryon} + \chi_i [+\text{meson(s)}],$$

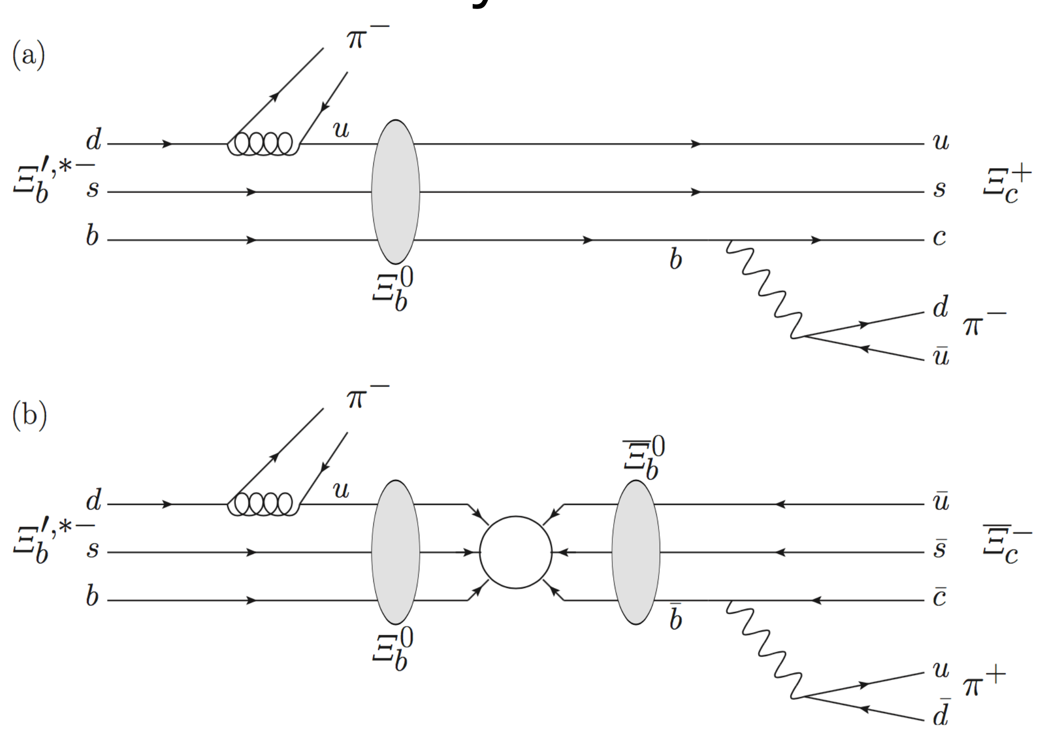
$$\text{baryon} \to \text{meson(s)} + \chi_i .$$

$$\Gamma_{b \to \chi_1 \bar{u} \bar{d}} \sim \frac{m_b \Delta m^4}{60\,(2\pi)^3} \left(\frac{g_{ub} y_{1d}}{m_\phi^2} \right)^2 + \mathcal{O}\left(\frac{\Delta m^5}{m_b^5} \right)$$

$$\simeq 2 \times 10^{-15}\ \text{GeV} \left(\frac{\Delta m}{2\ \text{GeV}} \right)^4 \left(\frac{1.2\ \text{TeV}}{m_\phi / \sqrt{g_{ub} y_{1d}}} \right)^4$$

branchings can be ~10^{-3}

Also look for baryon oscillations:



Search for baryon-number-violating Ξ_b^0 oscillations

LHCb collaboration [1708.05808]

$$P_{\mathcal{B} \to \bar{\mathcal{B}}} \sim \frac{|M_{12}|^2}{\Gamma_{\mathcal{B}}^2} \sim 10^{-5}$$

+displaced vertices…

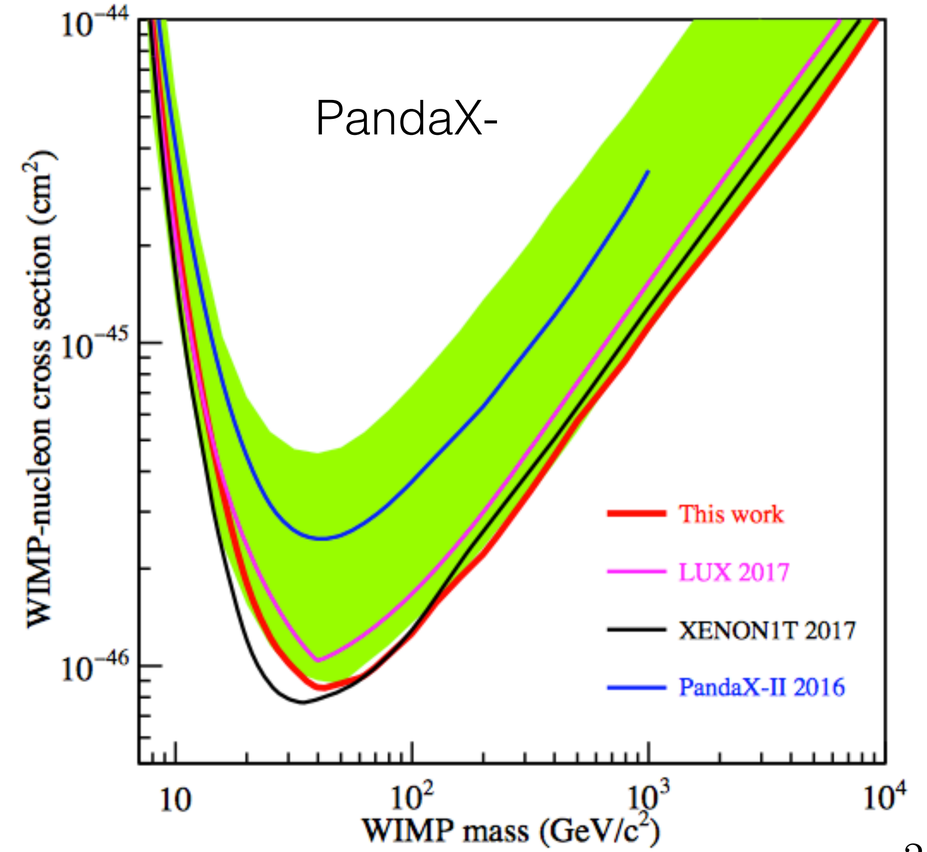
How about dark matter?

DM could interact via electroweak

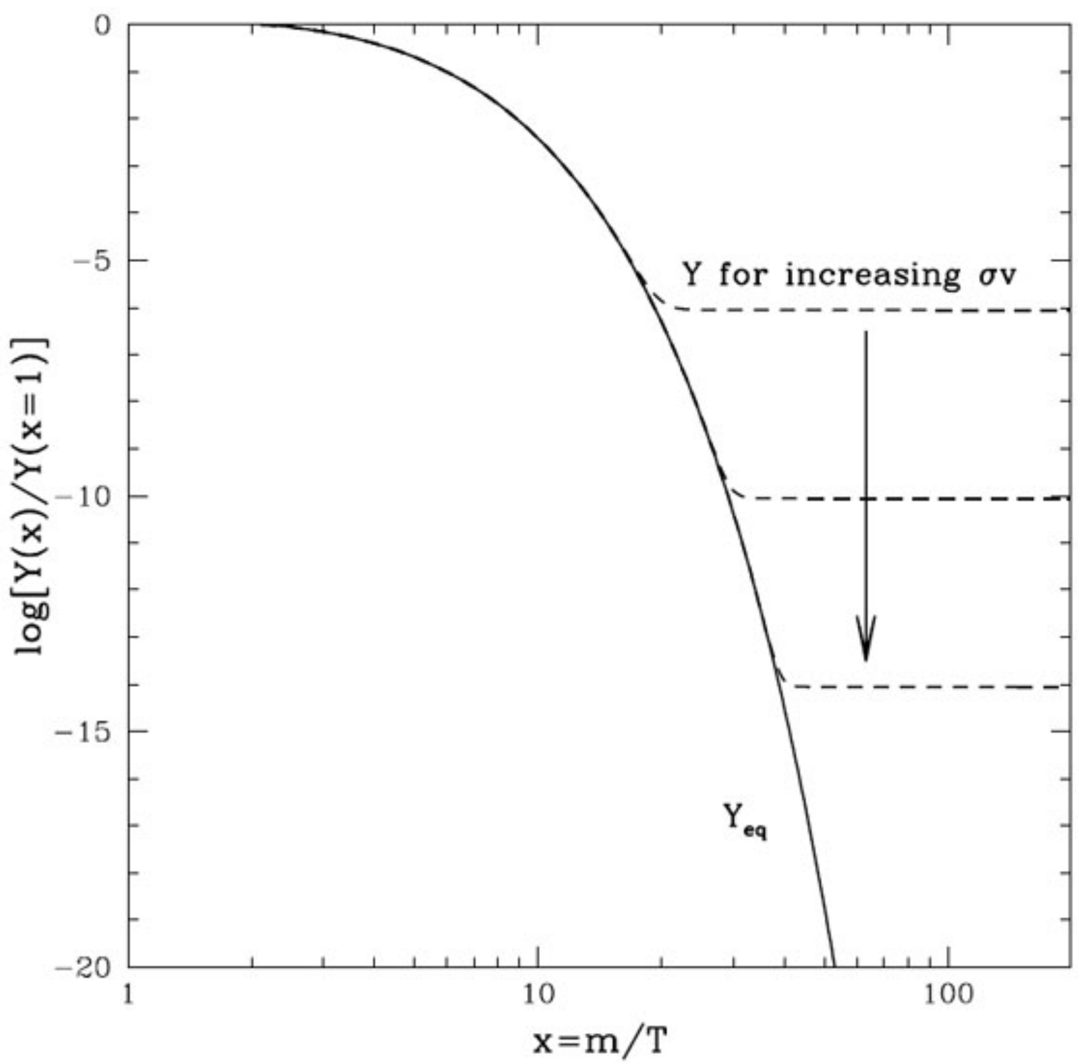
$$\Omega_{\rm DM} \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{m^2}{g^2}$$

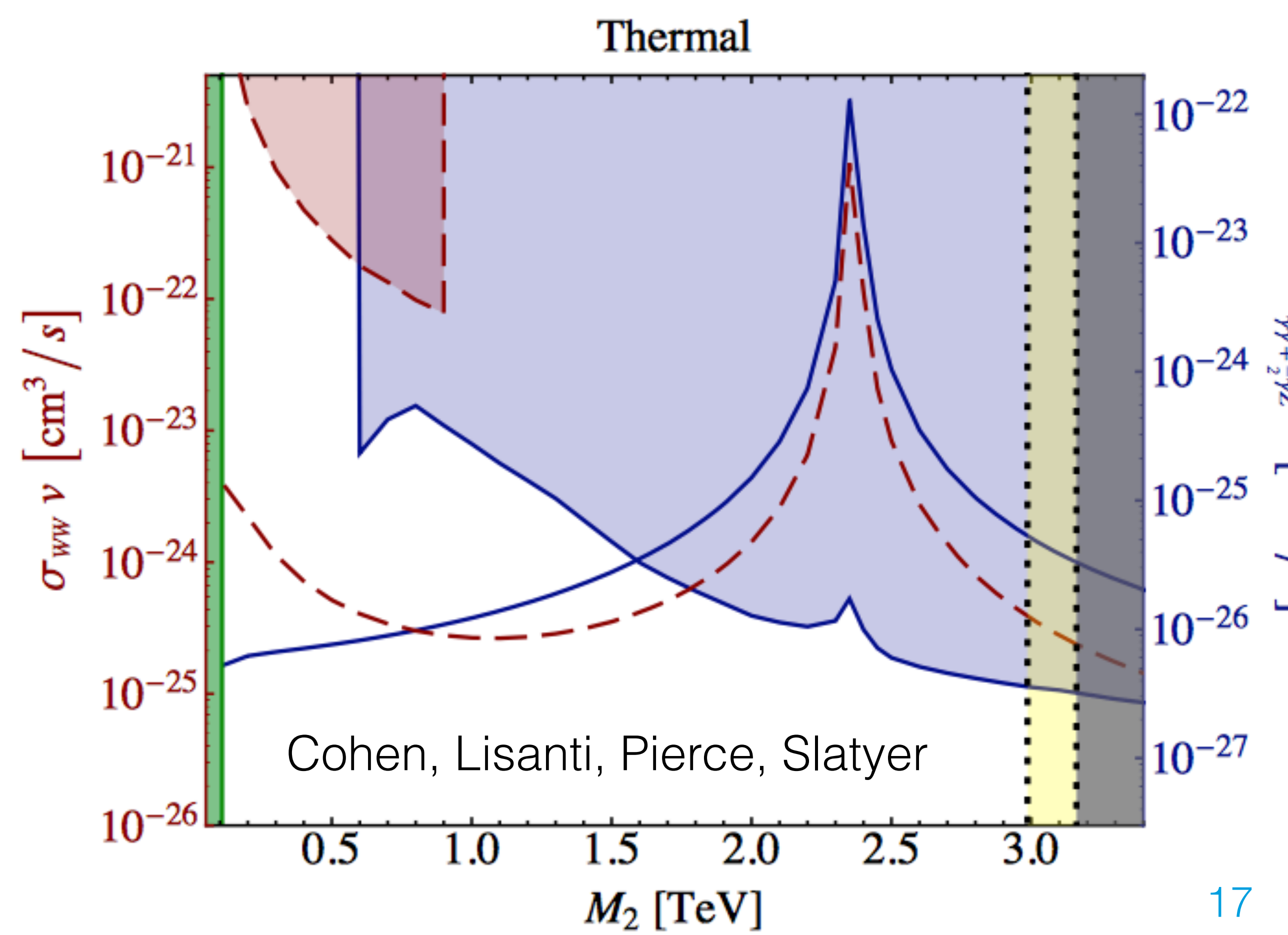
$$\sim 0.25 \left(\frac{m}{m_{\rm ew}}\right)^2 \left(\frac{g_{\rm ew}}{g}\right)^4$$

but…



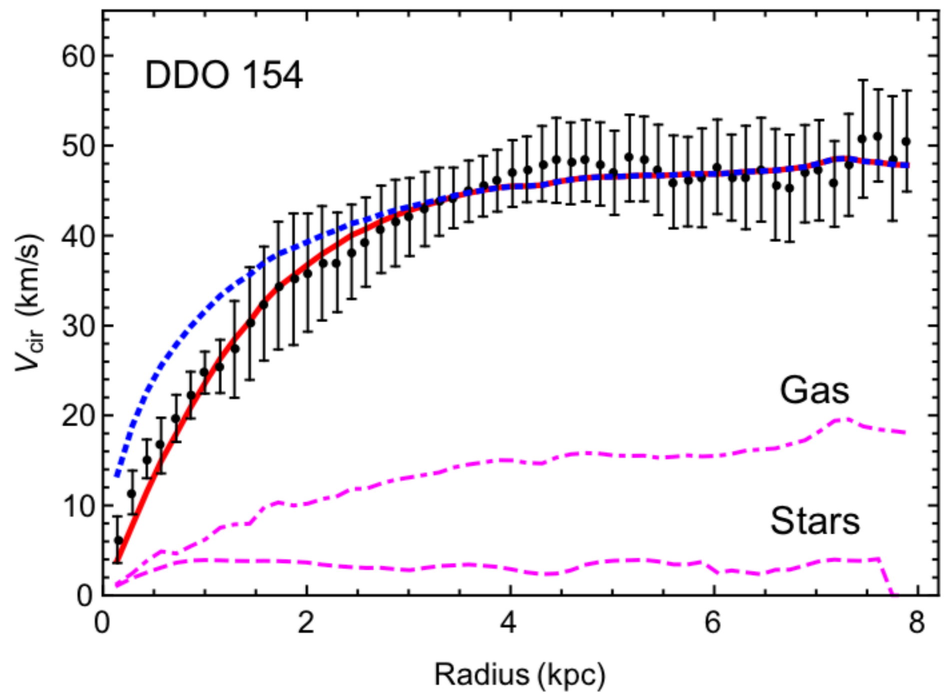
$$\sigma_{\rm DD} \sim \frac{G_F^2 \mu^2}{\pi} Y^2 \sim 10^{-39}\ {\rm cm}^2 \left(\frac{Y}{1/2}\right)^2$$

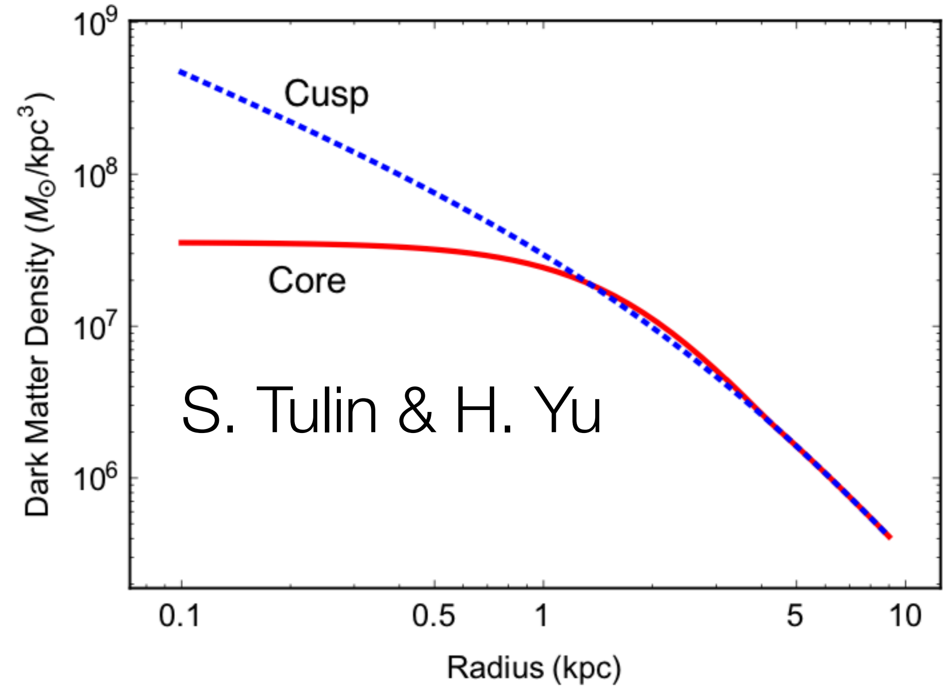




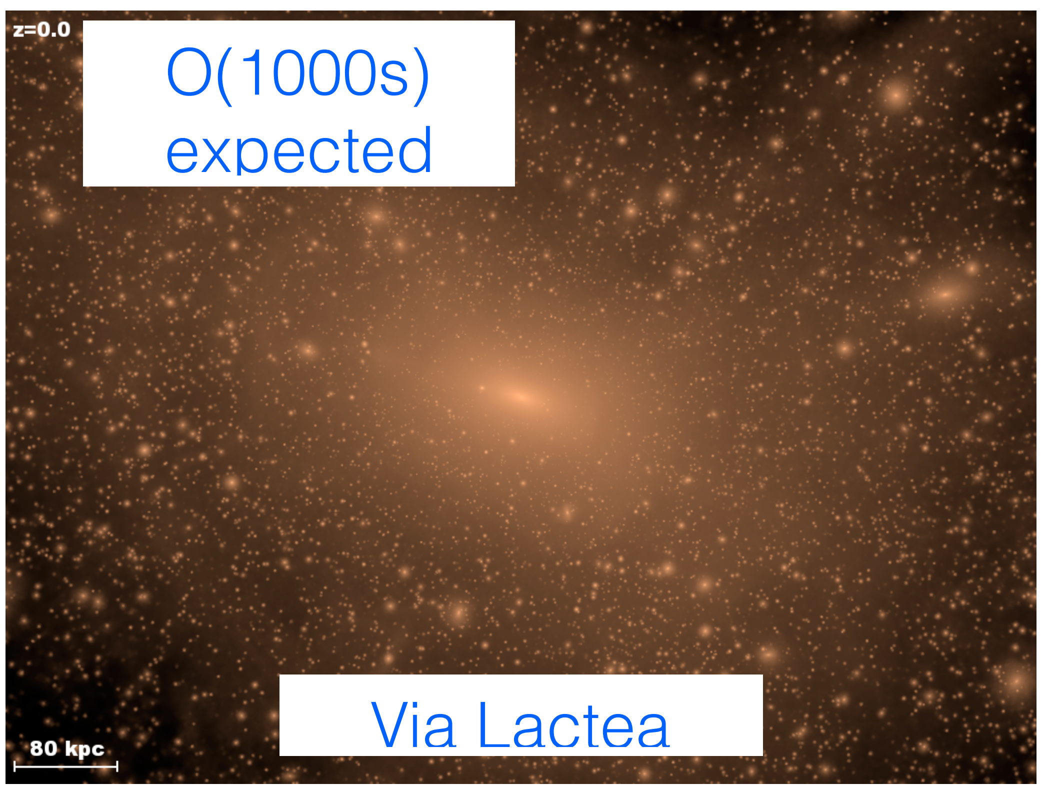
And…

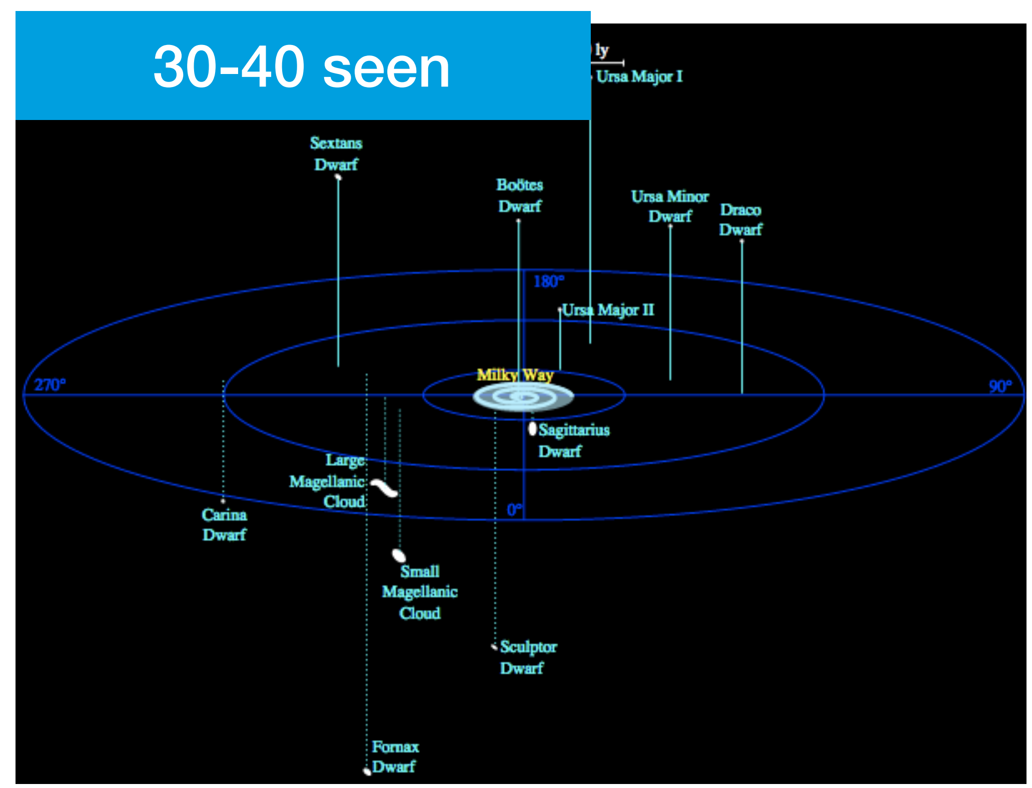
"Core vs. Cusp"





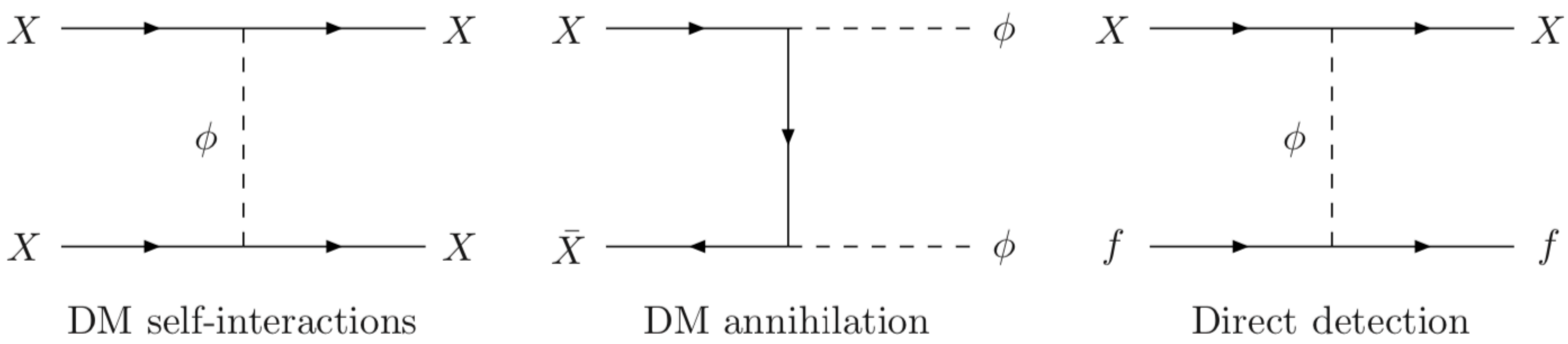
"Missing Satellites"



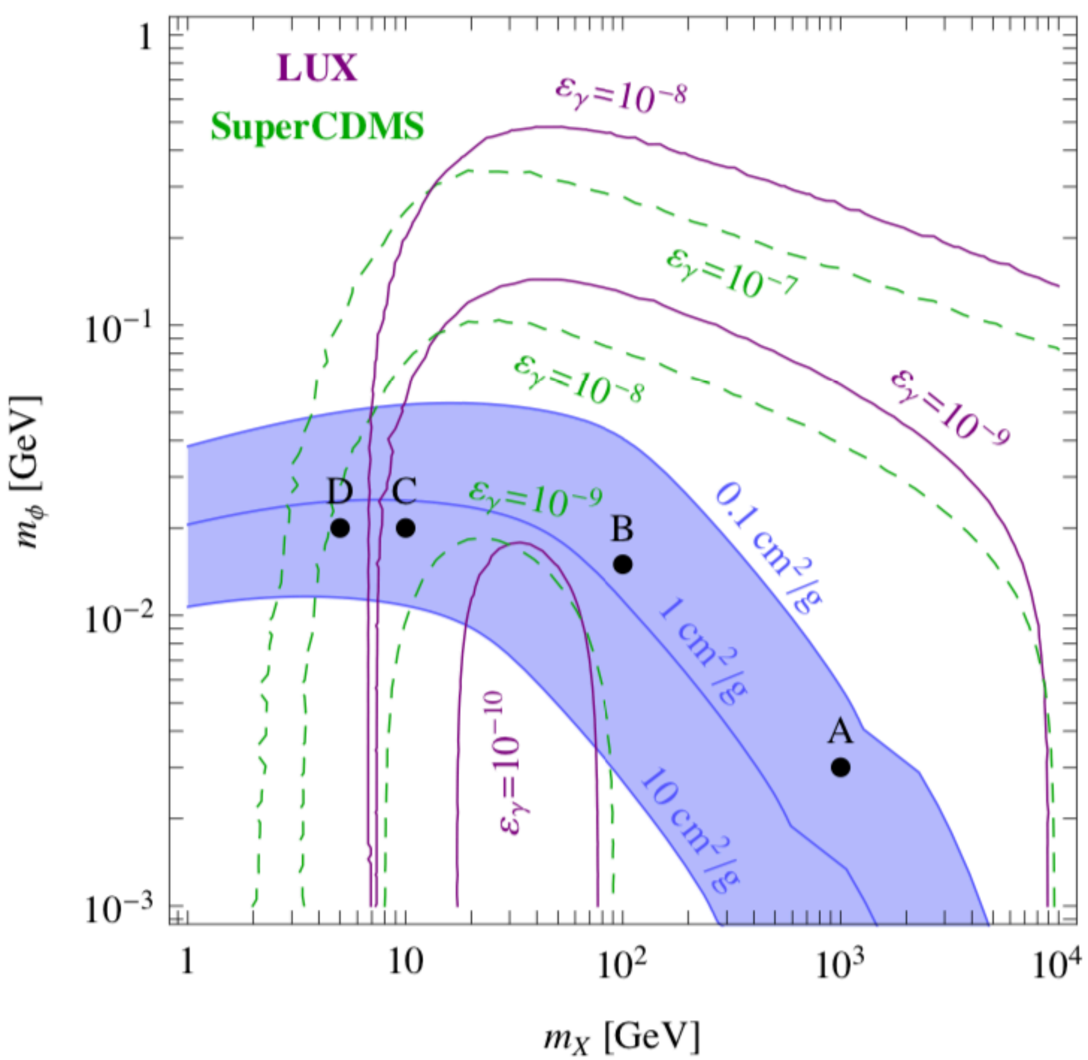


Cracks in "Cosmological Standard Model"?

Self-interacting DM



S. Tulin & H. Yu

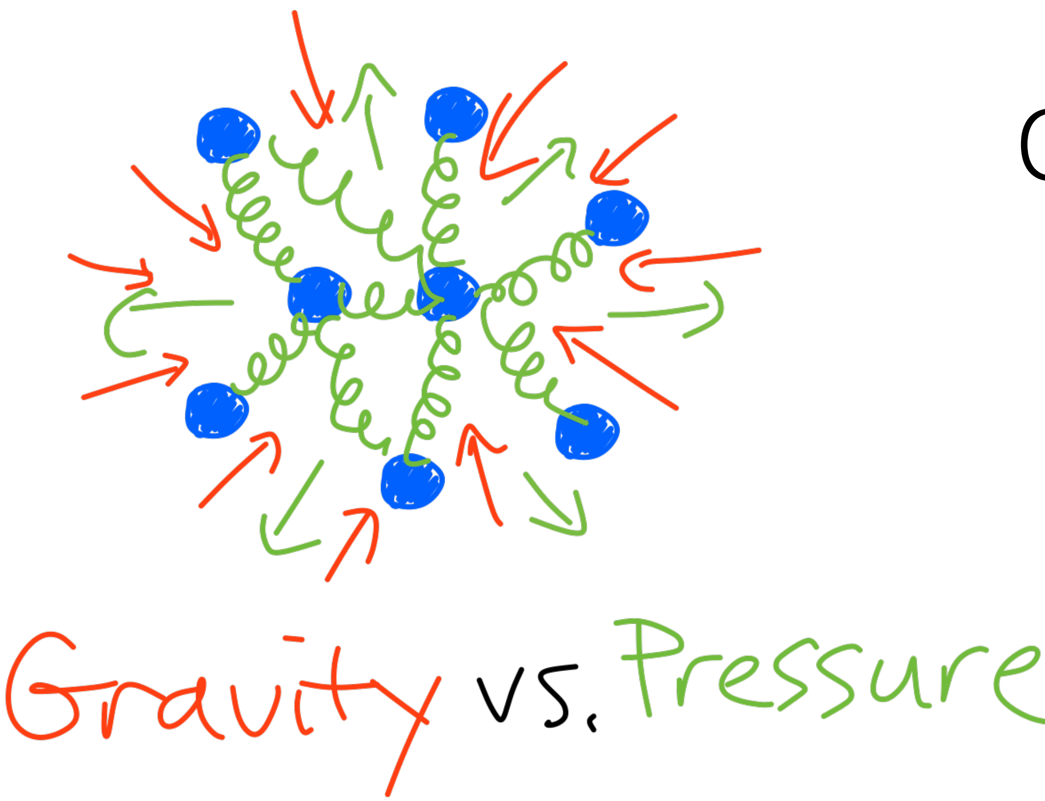


SIDM solutions to core-cusp often have light mediators, coupled to SM through "portals"

See talk by Brian Shuve next!

Structure formation

Basic physics that sets the scales of structure formation



Consider 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

A model for ν-DM interactions

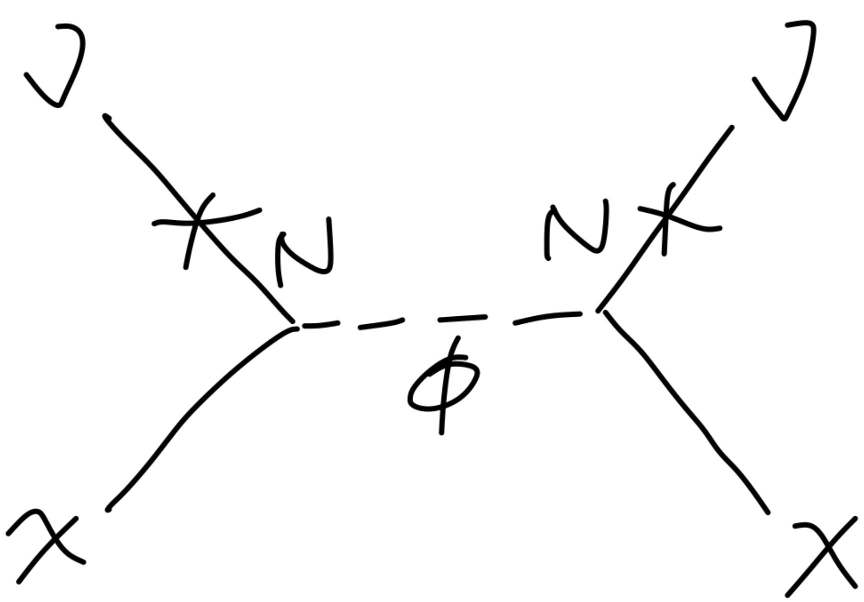
$$\mathcal{L} \supset -\lambda \bar{L} H N - y \bar{N} \chi \phi + \text{h.c.} \rightarrow -\lambda v \bar{\nu} N - y \bar{N} \chi \phi + \text{h.c.}$$

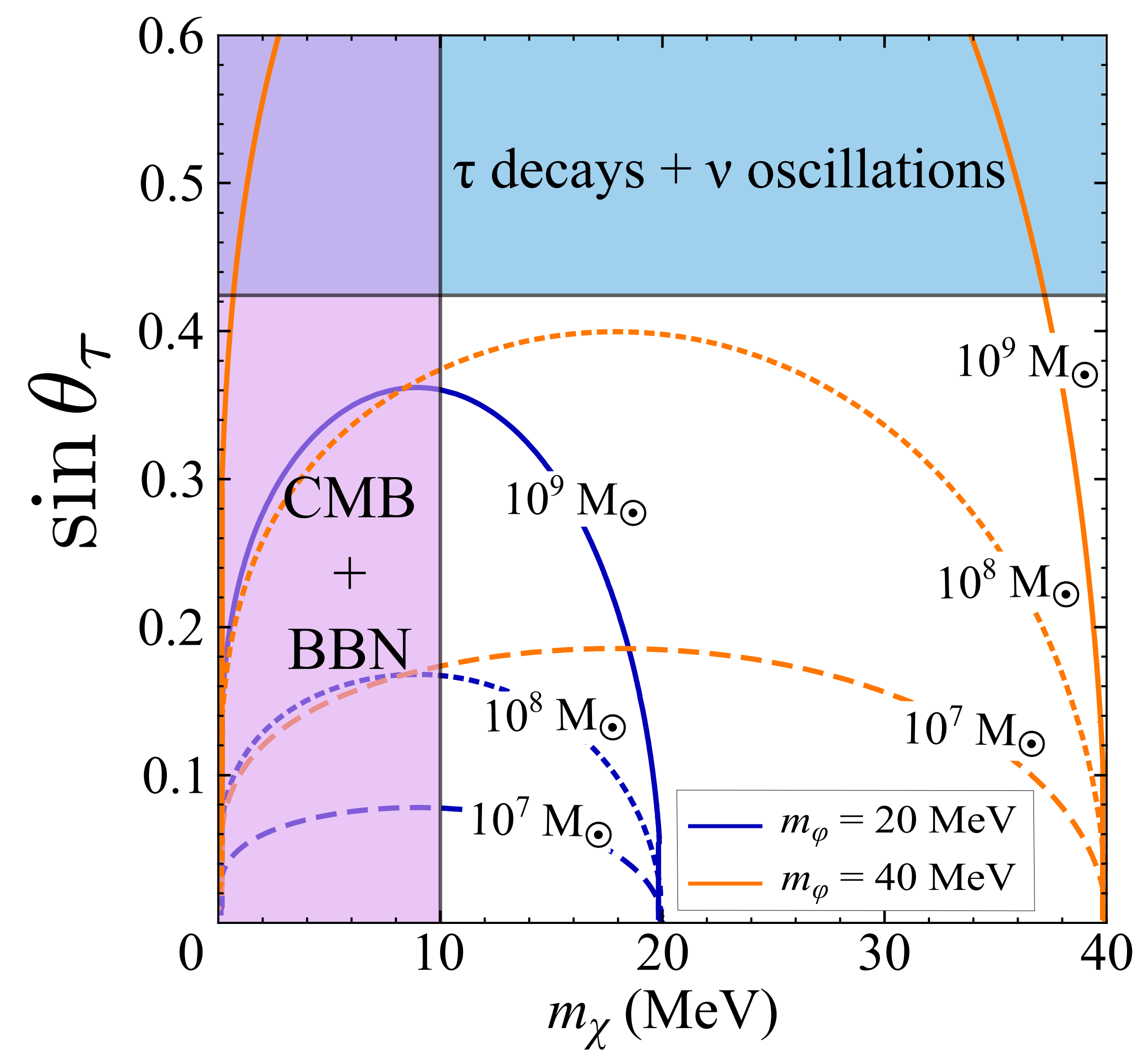
dark sector

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

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

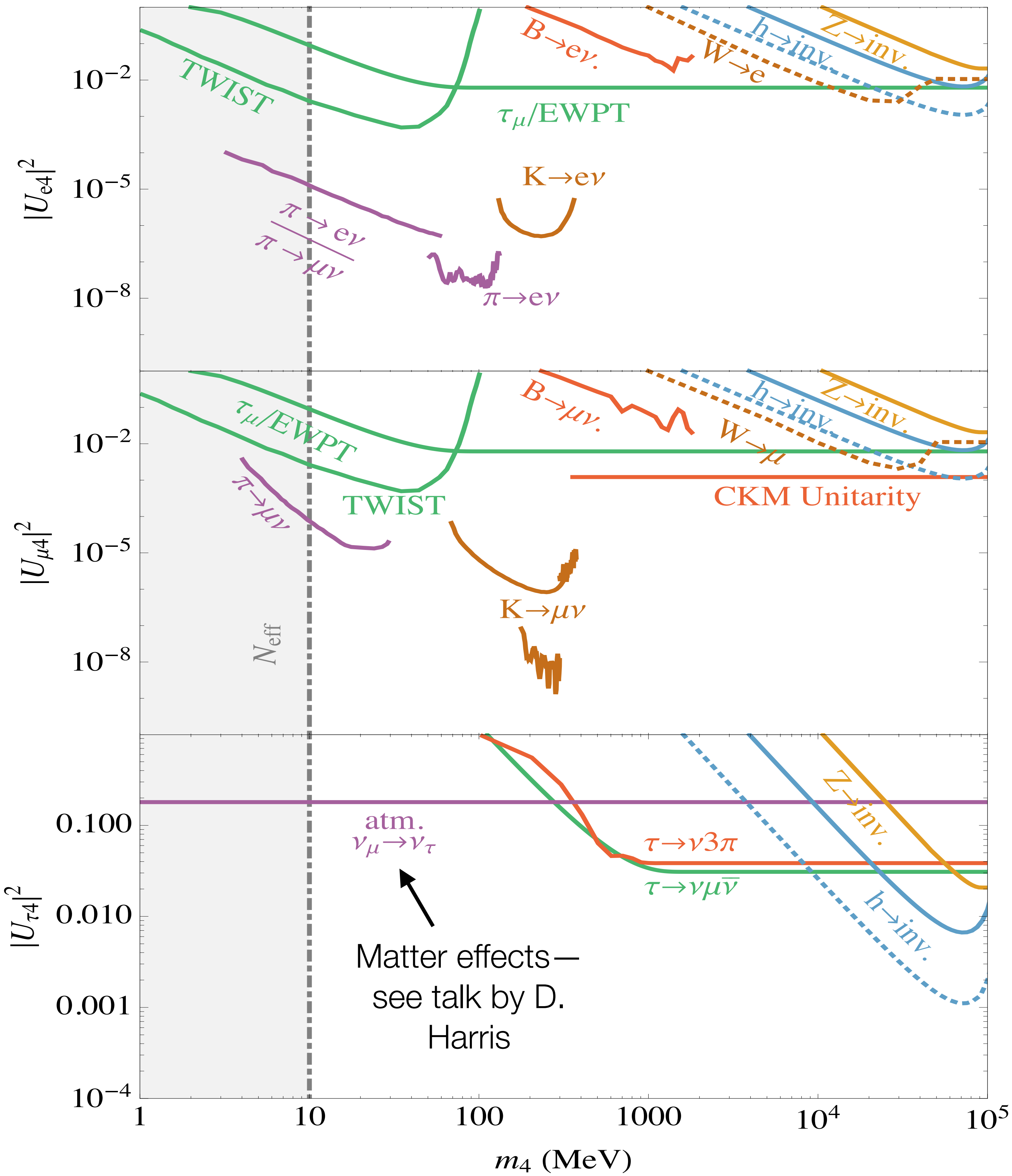
DM can scatter on light (mostly active) neutrinos



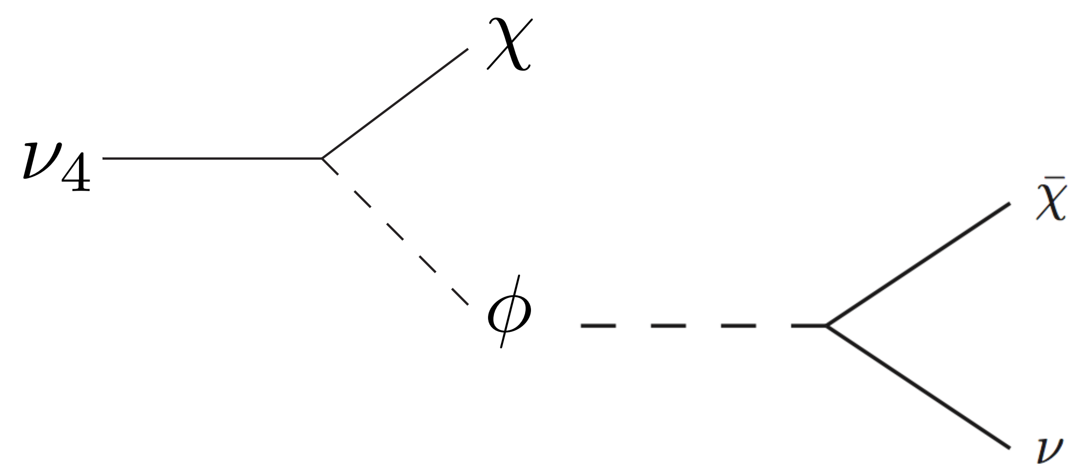


Bertoni, Ipek, DM, & Nelson

Mixing angle constraints



Heavy neutrinos decay (invisibly) through dark sector



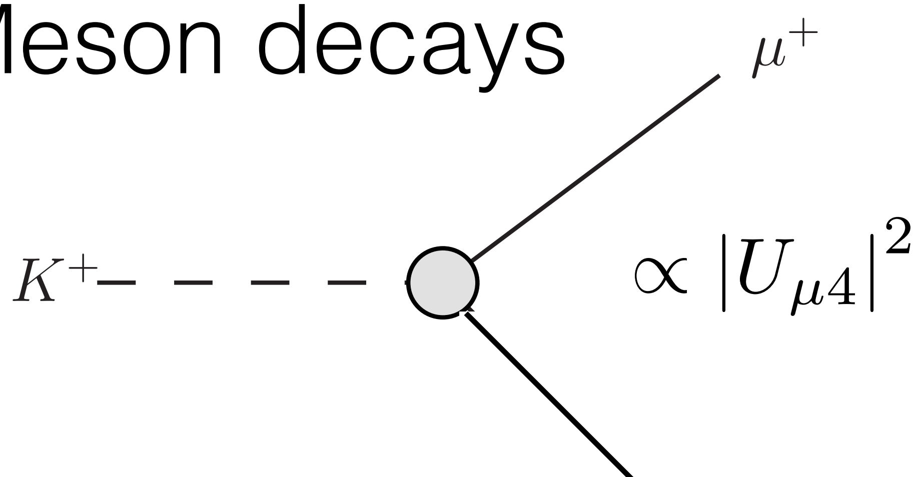
Fewer constraints than in visible decay case

τ sector less well probed

Bertoni, Ipek, DM, & Nelson 1412.3113
Batell, Han, DM, & Shams Es Haghi 1709.07001
De Gouvea & Kelly, …

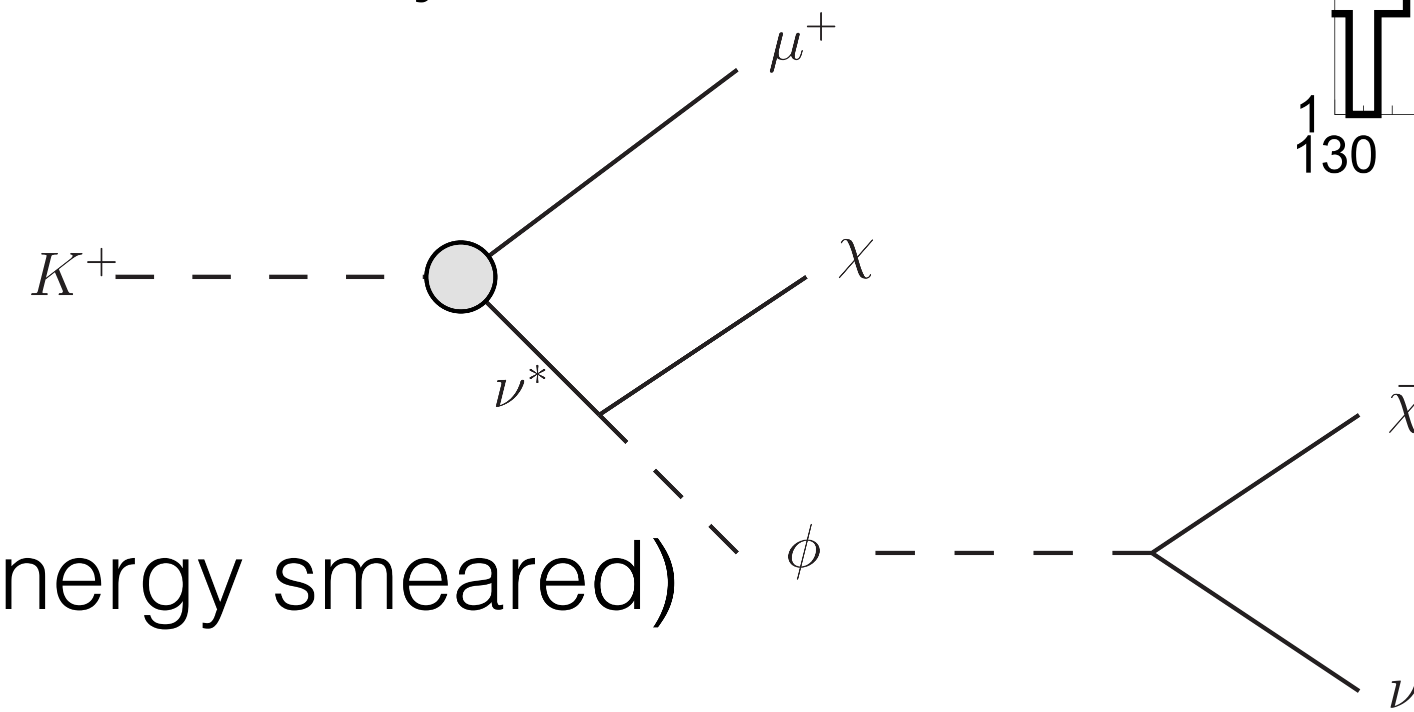
Probing with kinematics

Meson decays

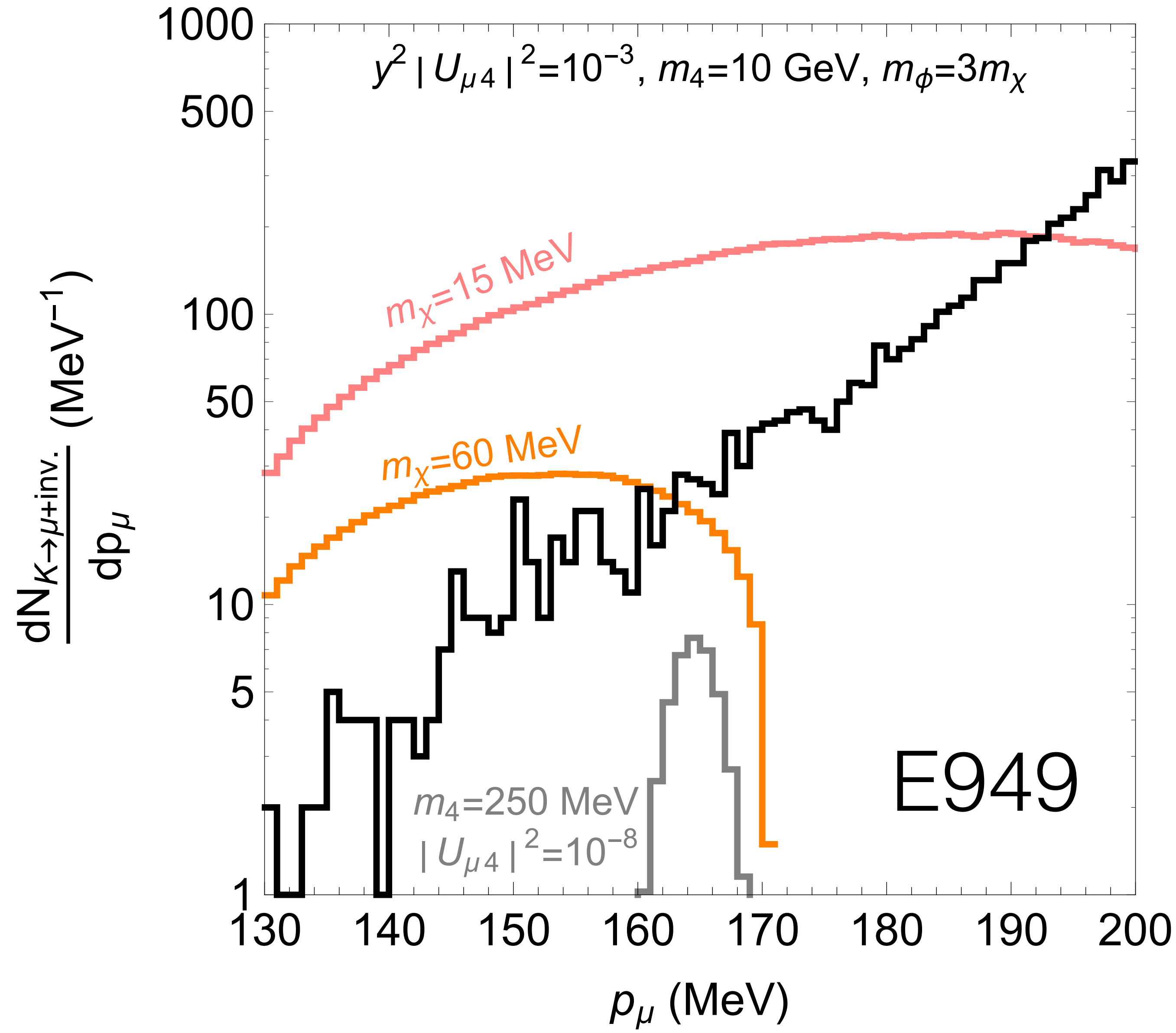


$$E_\mu = \frac{m_K^2 + m_\mu^2 - m_4^2}{2m_K}$$

Also decays into DM:



(μ energy smeared)

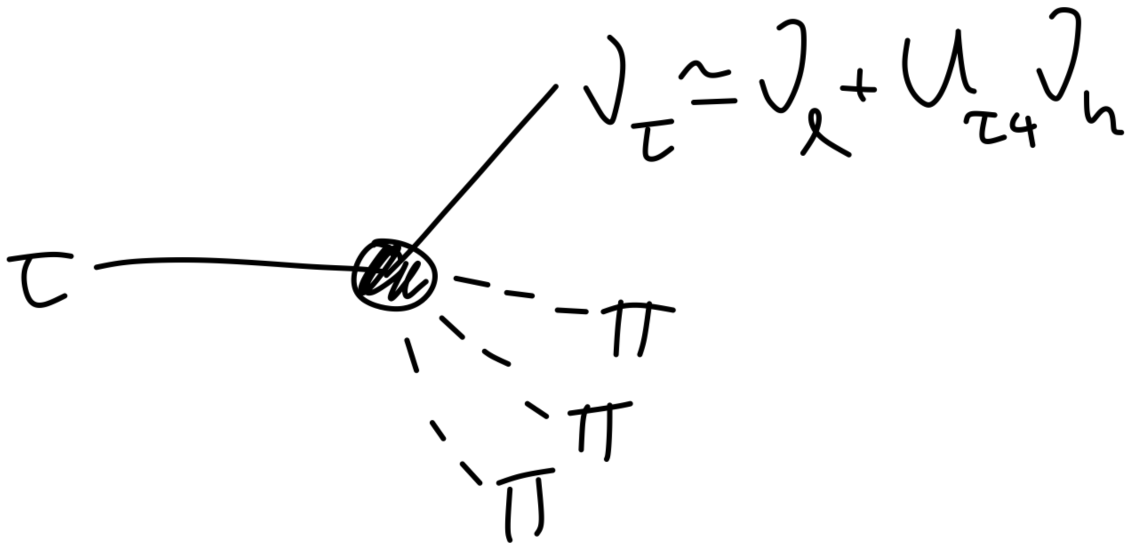


E949: 10^{12} kaons
NA62 increase by ~order of mag.

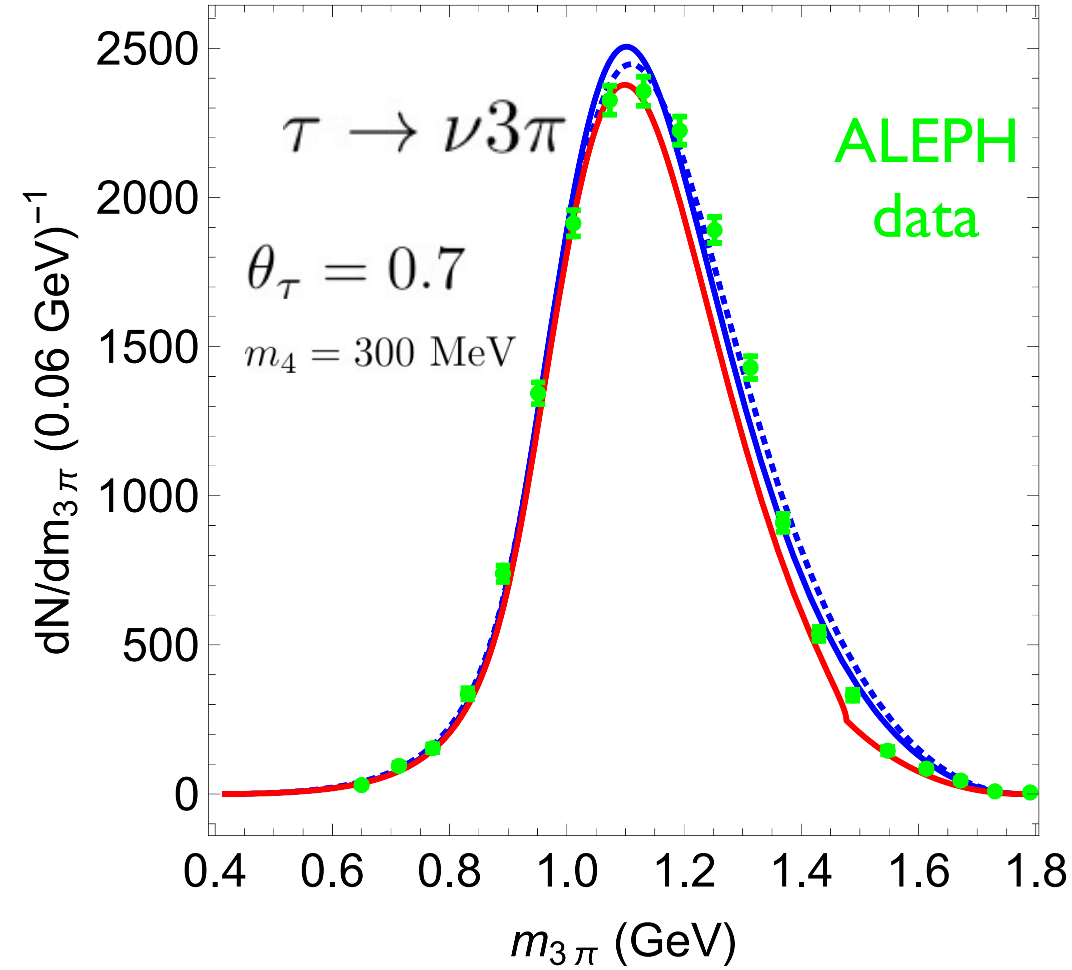
(See M. Zamkovsky's talk)

Taus are a good place to look

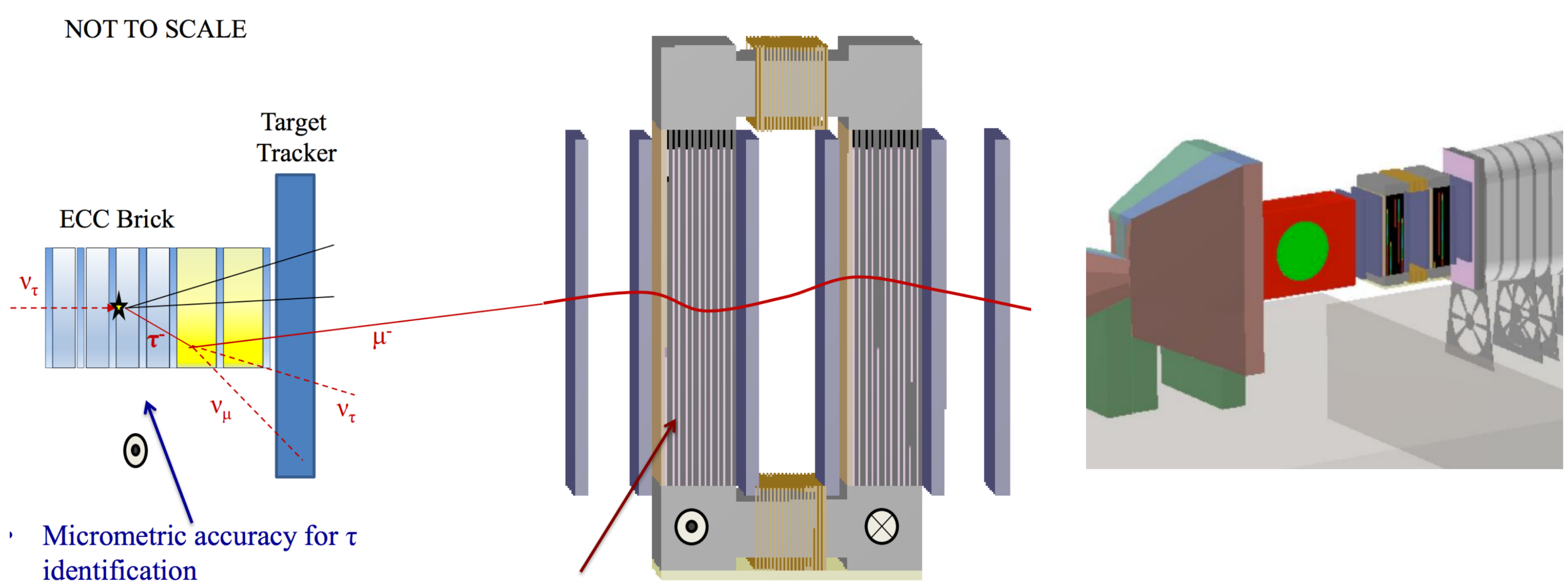
τ decays



Belle II: $0.8 \times 10^9 \ \tau^+\tau^- / \mathrm{ab}^{-1}$



What about O(3-4k) ν_τ sample at SHiP?



Conclusions

Only had time to show a (biased) sample of topics where cosmological observables have large interplay with those in "low energy" particle physics

There are a wealth of other examples

Flavour physics facilities have a lot to say about the baryon asymmetry of the Universe

Low energy particle physics experiments allow us to test non-CDM scenarios in arenas where the systematics are completely orthogonal

This is not the end of the story!

Backup

Baryon Candidates

Dinucleon decay constraints "unavoidable"

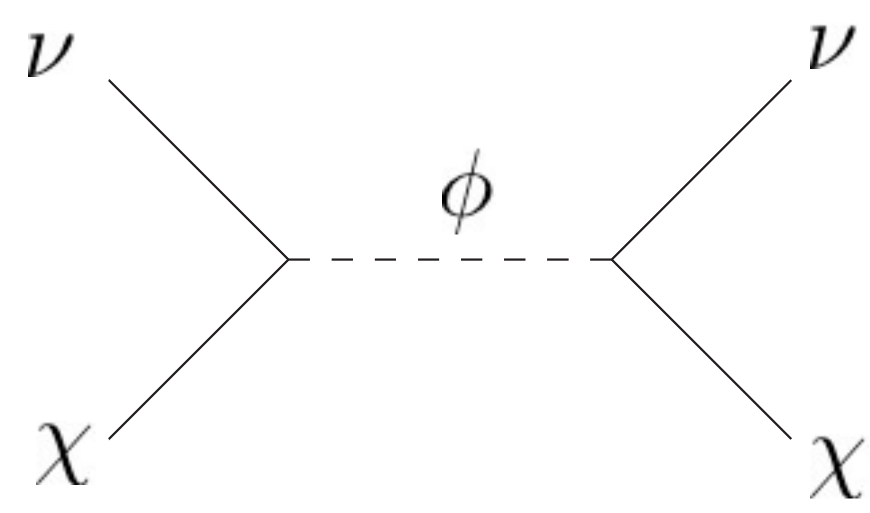
Collider constraints "model dependent"

Operator	$\mathcal{B}$	Weak Insertions Required	Measured Γ (GeV) [19]	Limits on $\delta_{\mathcal{B}\mathcal{B}} = M_{12}$ (GeV) Dinucleon decay	Collider
$(udd)^2$	n	None	$(7.477 \pm 0.009) \times 10^{-28}$	10^{-33}	10^{-17}
$(uds)^2$	Λ	None	$(2.501 \pm 0.019) \times 10^{-15}$	10^{-30}	10^{-17}
$(uds)^2$	Σ^0	None	$(8.9 \pm 0.8) \times 10^{-6}$	10^{-30}	10^{-17}
$(uss)^2$	Ξ^0	One	$(2.27 \pm 0.07) \times 10^{-15}$	10^{-22}	10^{-17}
$(ddc)^2$	Σ_c^0	Two	$(1.83^{+0.11}_{-0.19}) \times 10^{-3}$	10^{-17}	10^{-16}
$(dsc)^2$	Ξ_c^0	Two	$(5.87^{+0.58}_{-0.61}) \times 10^{-12}$	10^{-16}	10^{-15}
$(ssc)^2$	Ω_c^0	Two	$(9.5 \pm 1.2) \times 10^{-12}$	10^{-14}	10^{-15}
$(udb)^2$	Λ_b^0	Two	$(4.490 \pm 0.031) \times 10^{-13}$	10^{-13}	10^{-17}
$(udb)^2$	Σ_b^{0*}	Two	$\sim 10^{-3*}$	10^{-13}	10^{-17}
$(usb)^2$	Ξ_b^0	Two	$(4.496 \pm 0.095) \times 10^{-13}$	10^{-10}	10^{-17}
$(dcb)^2$	${\Xi_{cb}^0}^\dagger$	Two	$\sim 10^{-12\dagger}$	10^{-17}	10^{-15}
$(scb)^2$	${\Omega_{cb}^0}^\dagger$	Two	$\sim 10^{-12\dagger}$	10^{-14}	10^{-15}
$(ubb)^2$	${\Xi_{bb}^0}^\ddagger$	Four	$\sim 10^{-13\ddagger}$	>1	10^{-17}
$(cbb)^2$	${\Omega_{cbb}^0}^\dagger$	Four	$\sim 10^{-12\dagger}$	>1	10^{-15}

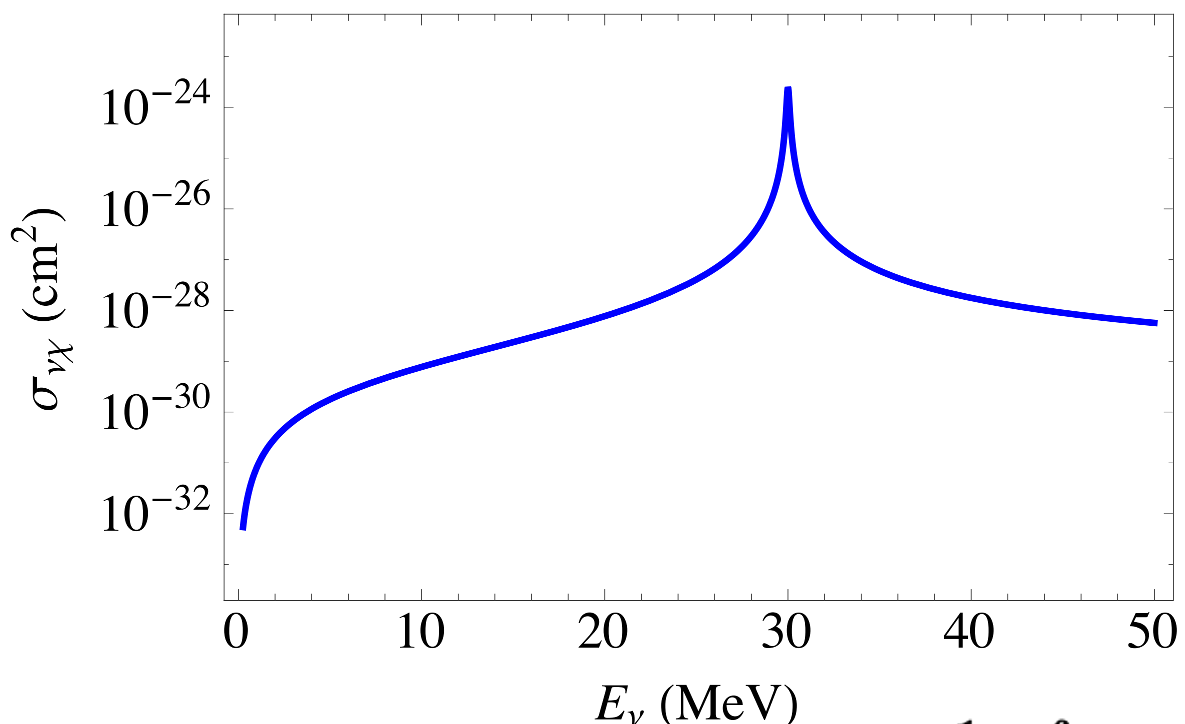
Other Probes?

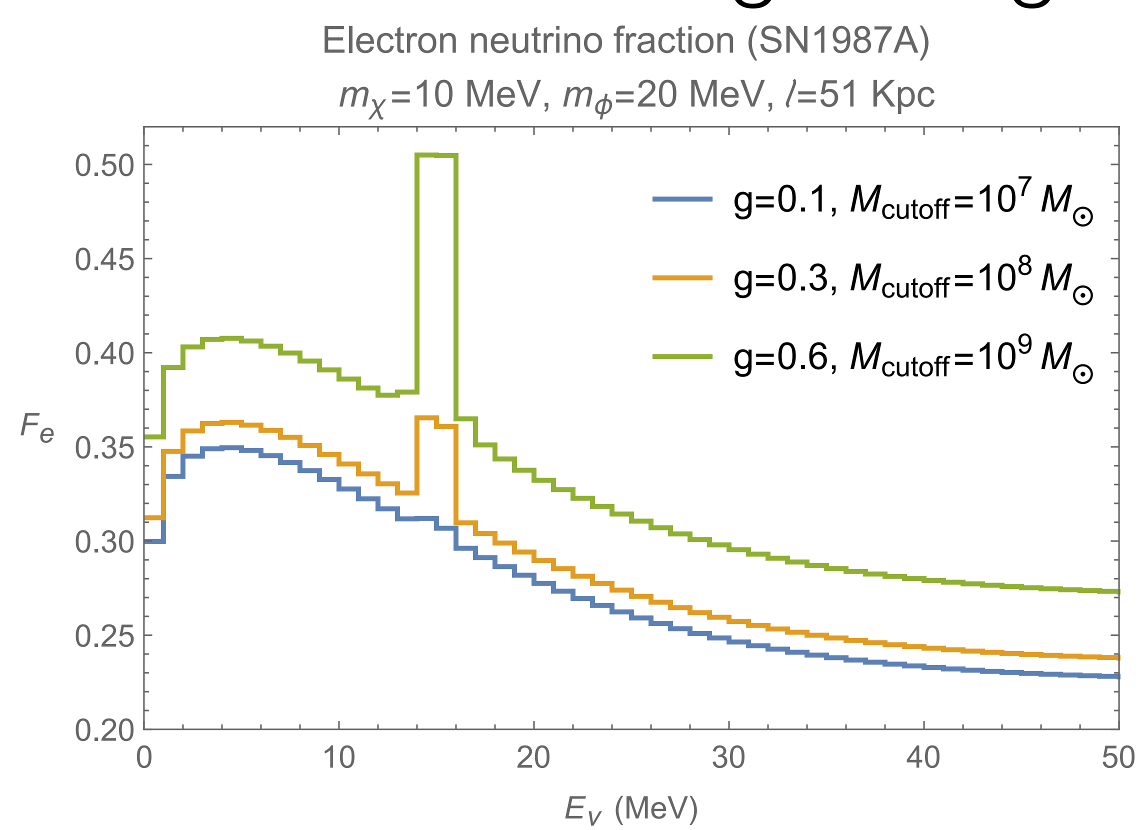
Supernova neutrinos

MeV energy neutrinos
from SN scatter on DM



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





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

(Study of effect on SNe complicated,
ongoing with Nirmal Raj)

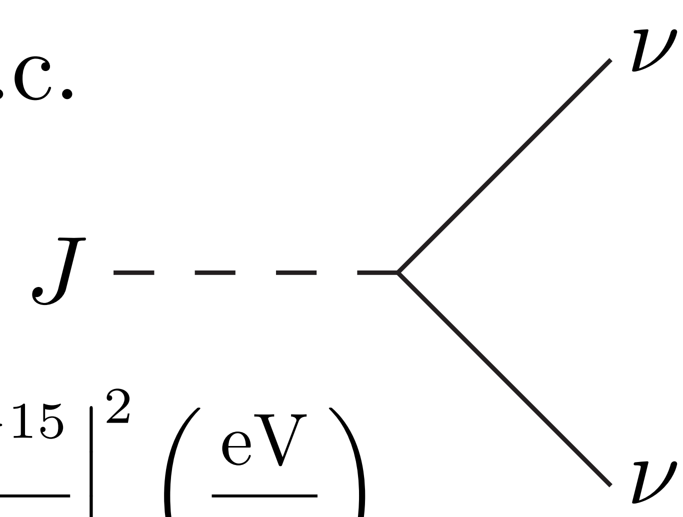
DM 1812.08178; Chacko, Du, & Geller 1812.11154

A very simple model

(Some of the) Dark Matter weakly coupled to neutrinos, similar to majoron

$$\mathcal{L}_{\rm int} = -\frac{g}{2} J\nu\nu + \text{h.c.}$$

This state decays to (only) neutrinos



$$\tau_J = \frac{32\pi}{|g|^2 m_J} = 2.10 \times 10^9 \text{ yr} \left|\frac{10^{-15}}{g}\right|^2 \left(\frac{\text{eV}}{m_J}\right)$$

Neutrinos redshift until today

$$E_\nu \simeq \frac{m_J}{2} \frac{a_{\rm decay}}{a_{\rm today}}$$

What sort of flux can we imagine?

DM 1812.08178; Chacko, Du, & Geller 1812.11154

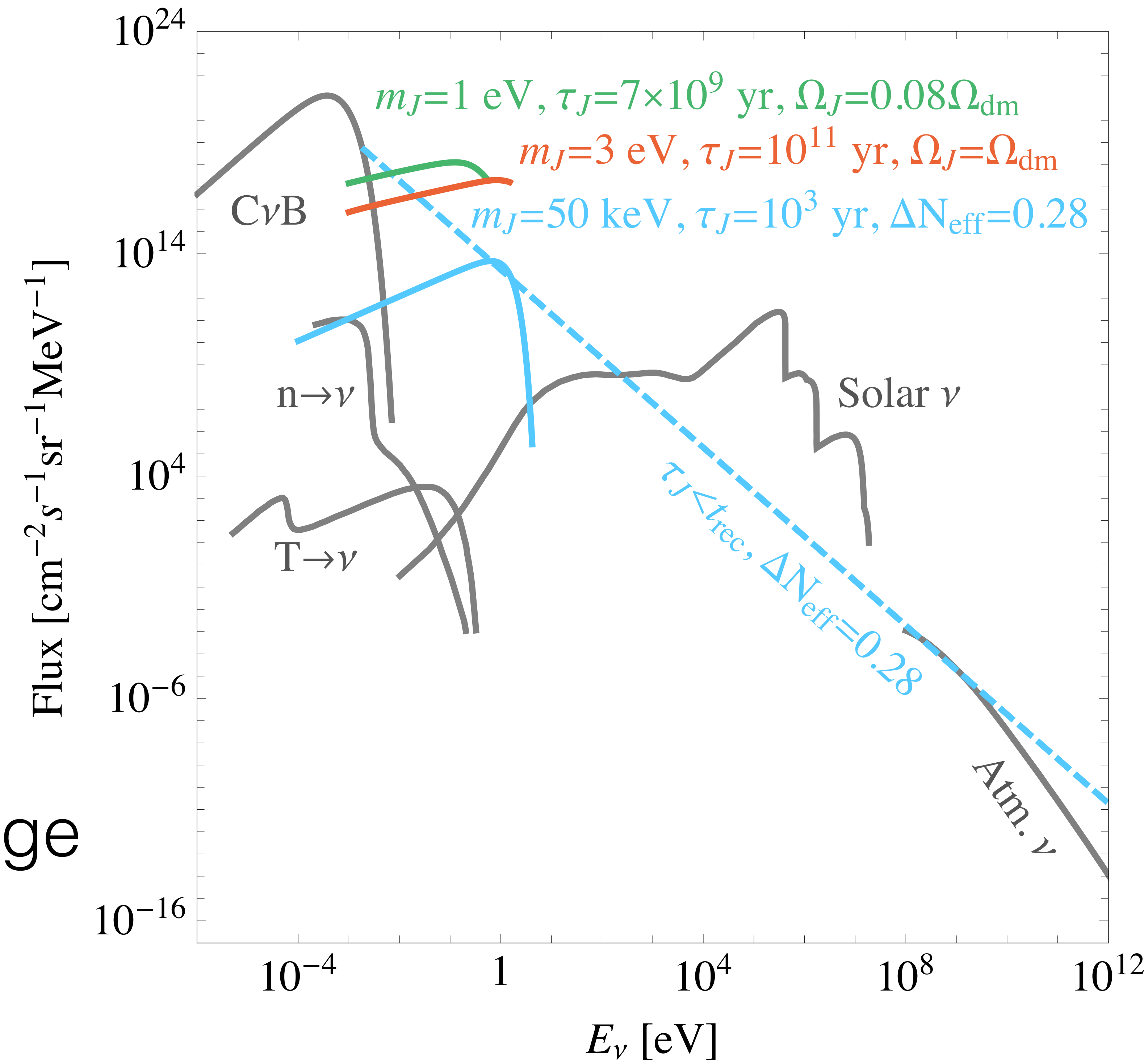
Potential Fluxes

Flux is given by

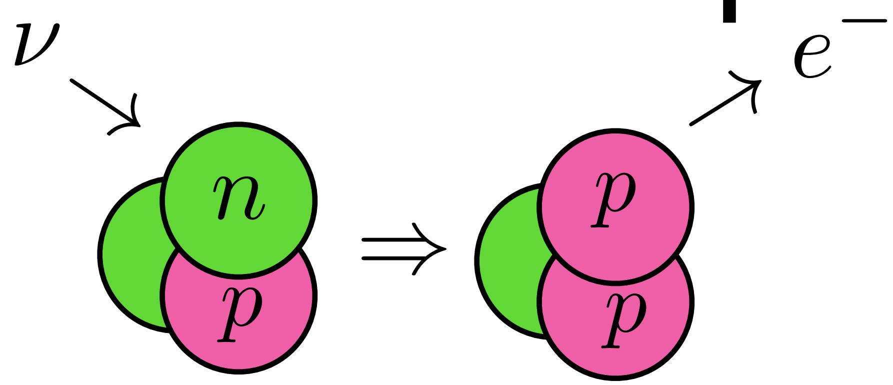
$$\tilde{\Phi}_\nu = \frac{d(a^3 \tilde{n}_\nu)}{dE_\nu}\Big|_{a=2E_\nu/m_J}$$

$$= \frac{2\,\Omega_J}{E_\nu}\,\frac{\rho_{\text{cr},0}}{m_J}\,\frac{e^{-t/\tau_J}}{H\tau_J}$$

Width determined by range of redshifts for decay



CνB capture on Tritium

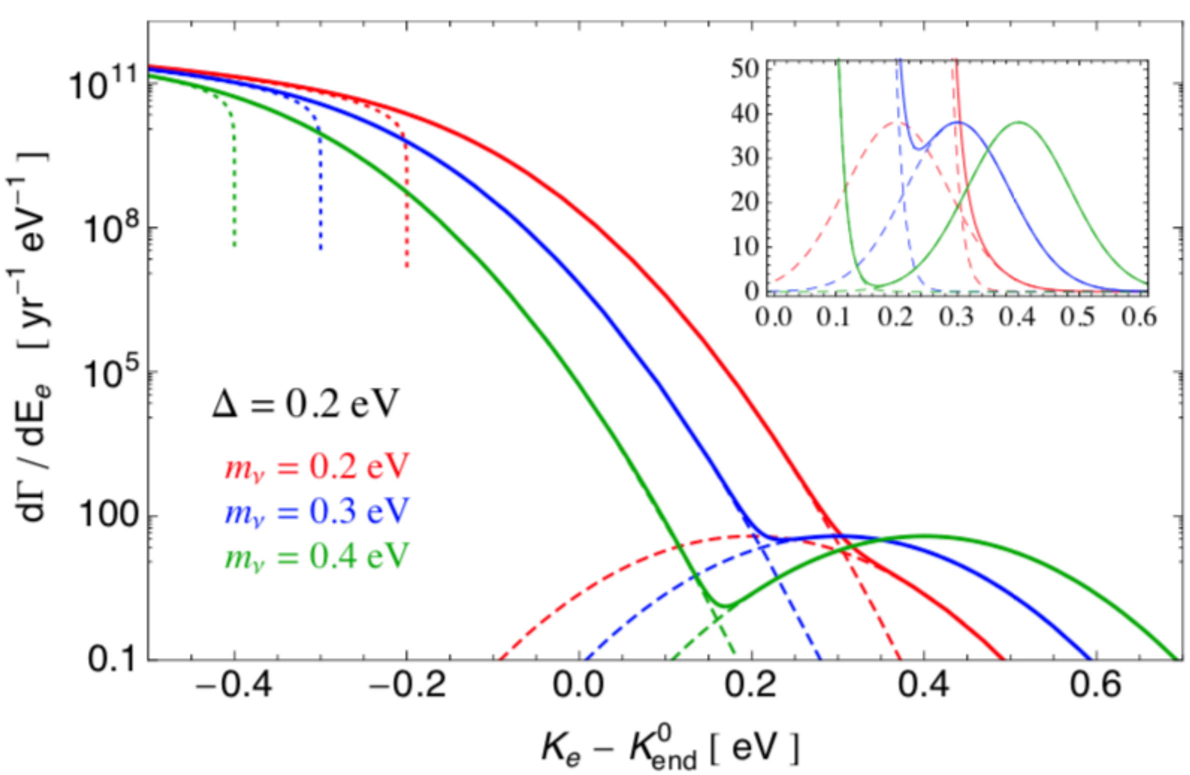


β-decays with long lifetime

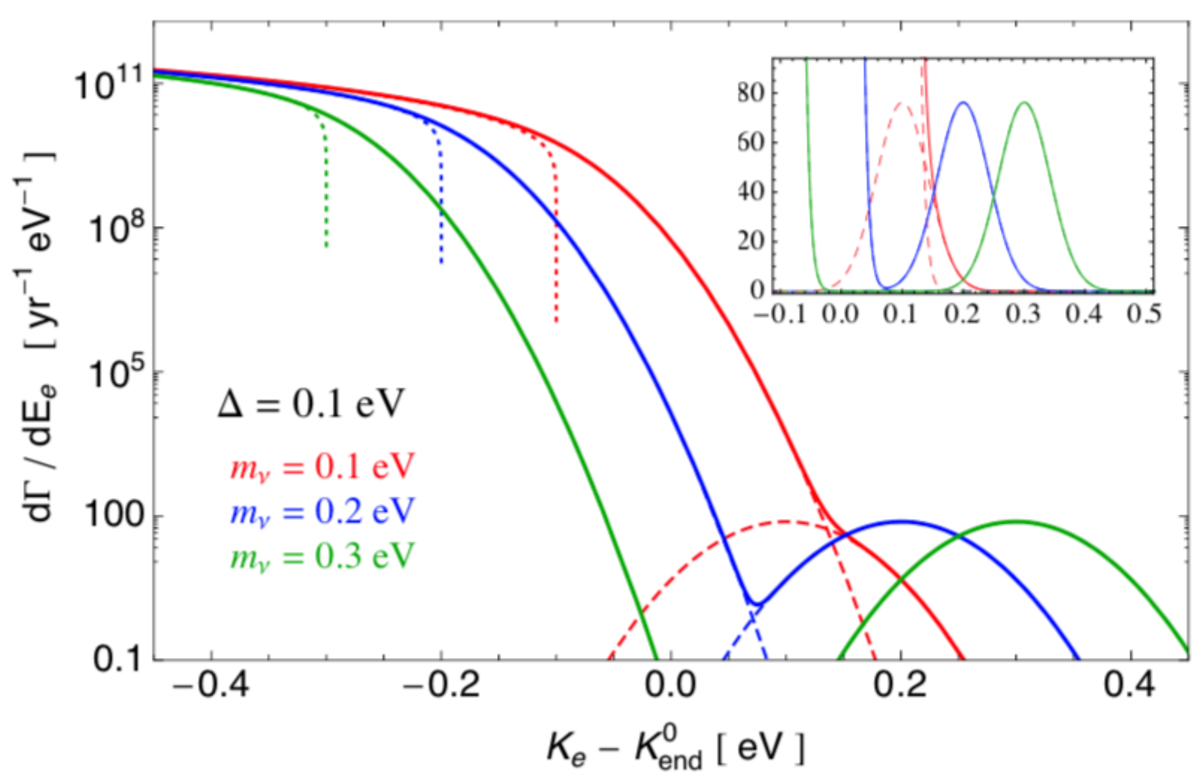
$$t_{1/2} \simeq 12 \text{ yr}$$

$$\sigma = 3.8 \times 10^{-45} \text{ cm}^2 \quad \Rightarrow \Gamma_{\text{Dir.}} = \frac{1}{2}\Gamma_{\text{Maj.}} = \frac{4}{\text{yr}} \left(\frac{M_T}{100 \text{ g}}\right) \left(\frac{n_\nu}{56 \text{ cm}^{-3}}\right)$$

PTOLEMY Experiment (100 g T)



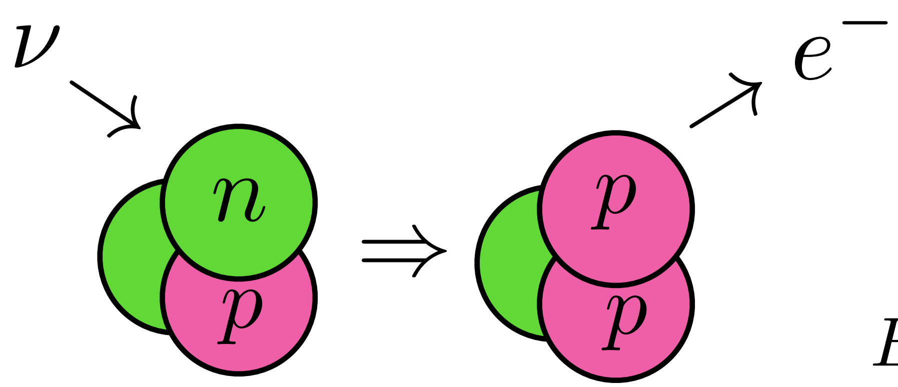
Long, Lunardini, Sabancilar



Tiny rates but a crucial target

DM 1812.08178; Chacko, Du, & Geller 1812.11154

ν from DM decay on Tritium

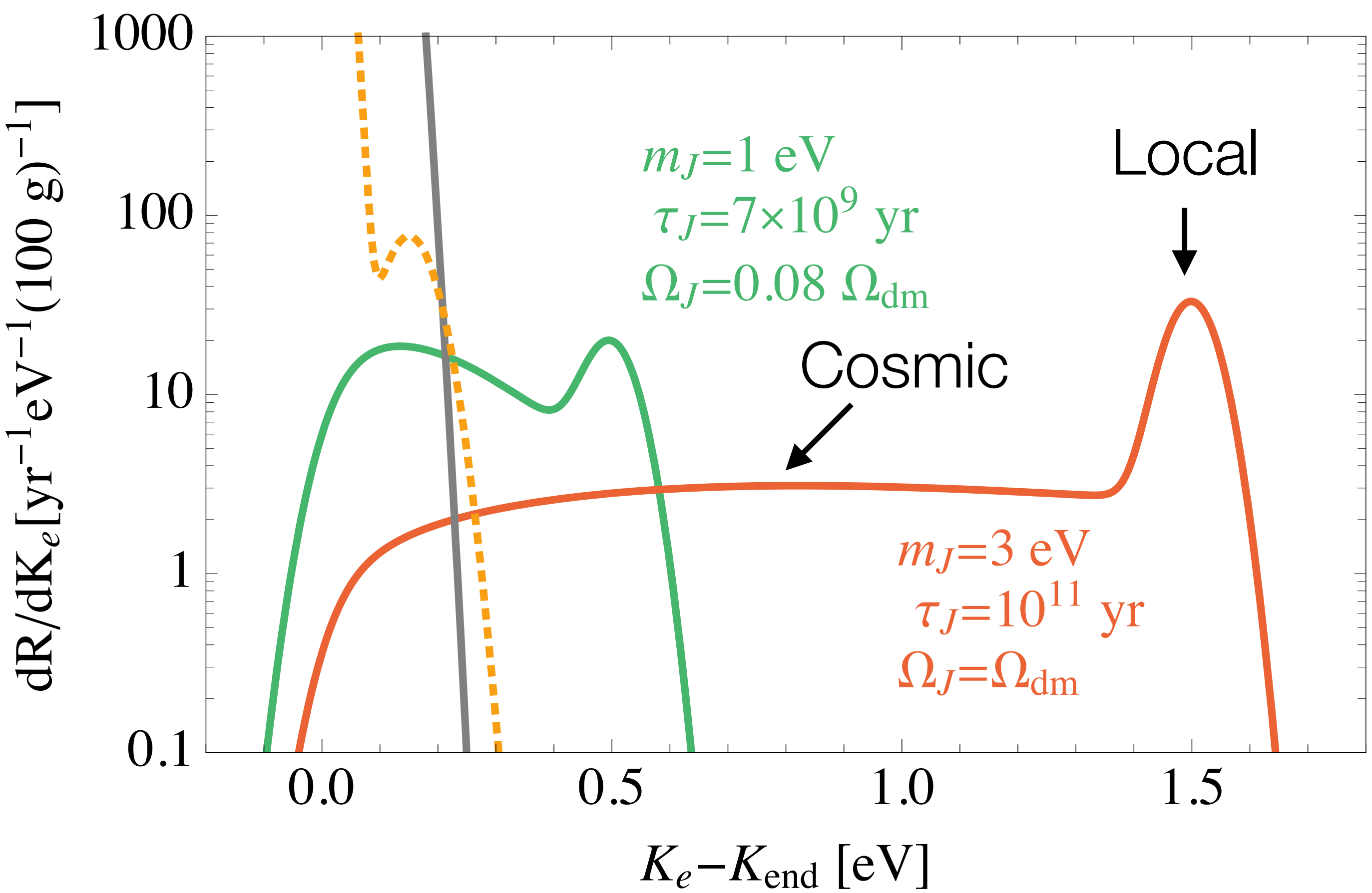


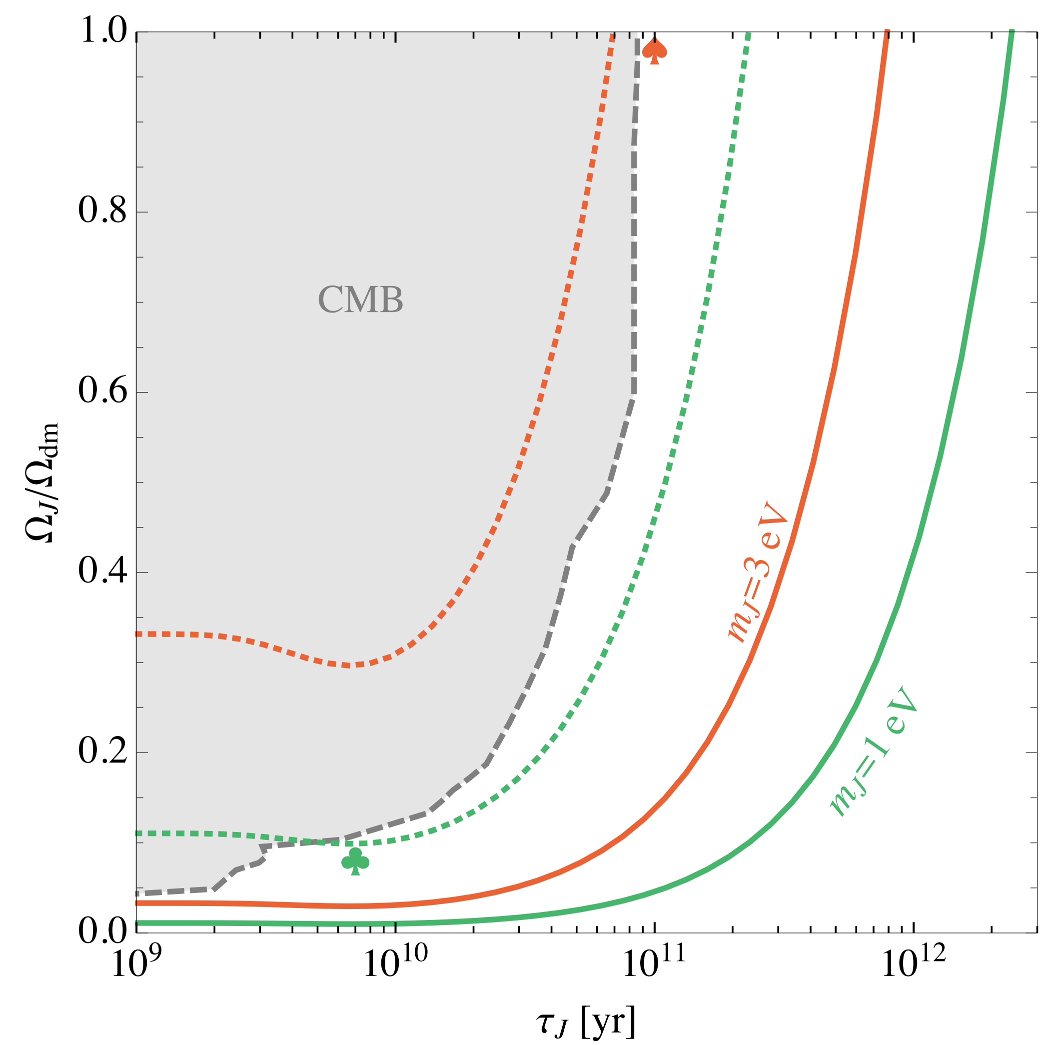
The electron energy gap can be larger in this case

$$E_{e^-} = E_{\rm end} + m_\nu + E_\nu \simeq E_{\rm end} + m_\nu + \frac{m_J}{2}\frac{a_{\rm decay}}{a_{\rm today}}$$

$$\tilde{n}_\nu \sim \frac{10}{\rm cm^3}\left(\frac{10\ \rm eV}{m_J}\right) \qquad \tau_J > t_{\rm rec}$$

$$R = \frac{2.42}{\rm yr}\left(\frac{M_T}{100\ \rm g}\right)\left(\frac{f_{\nu_e}}{1/3}\right)\left(\frac{\tilde{n}_\nu}{100\ \rm cm^3}\right)$$





Baryogenesis via flavon decays

Chen, Ipek, & Ratz 1903.06211

Froggatt-Nielsen model

$$\mathscr{L} \supset y_0^{fg} \left(\frac{v_S + S}{\Lambda}\right)^{n_{fg}} \bar{e}_{\mathrm{R}}^{g} \cdot \phi^* \cdot \ell_{\mathrm{L}}^{f} + \mathrm{h.c.}$$

(Arise in a "theory of flavor")

Flavon/antiflavon decay:

$$S \to \bar{\ell}_{\mathrm{L}} + \phi + e_{\mathrm{R}}$$

$$S^* \to \ell_{\mathrm{L}} + \phi^* + \bar{e}_{\mathrm{R}}$$

Flavon-antiflavon asymmetry ⇒ Left-handed lepton asymmetry ⇒ Turned into baryon asymmetry via sphalerons

1-10 TeV scale flavors required: