Neutrinos Faking Dark Matter (And Vice Versa)

Ian M. Shoemaker

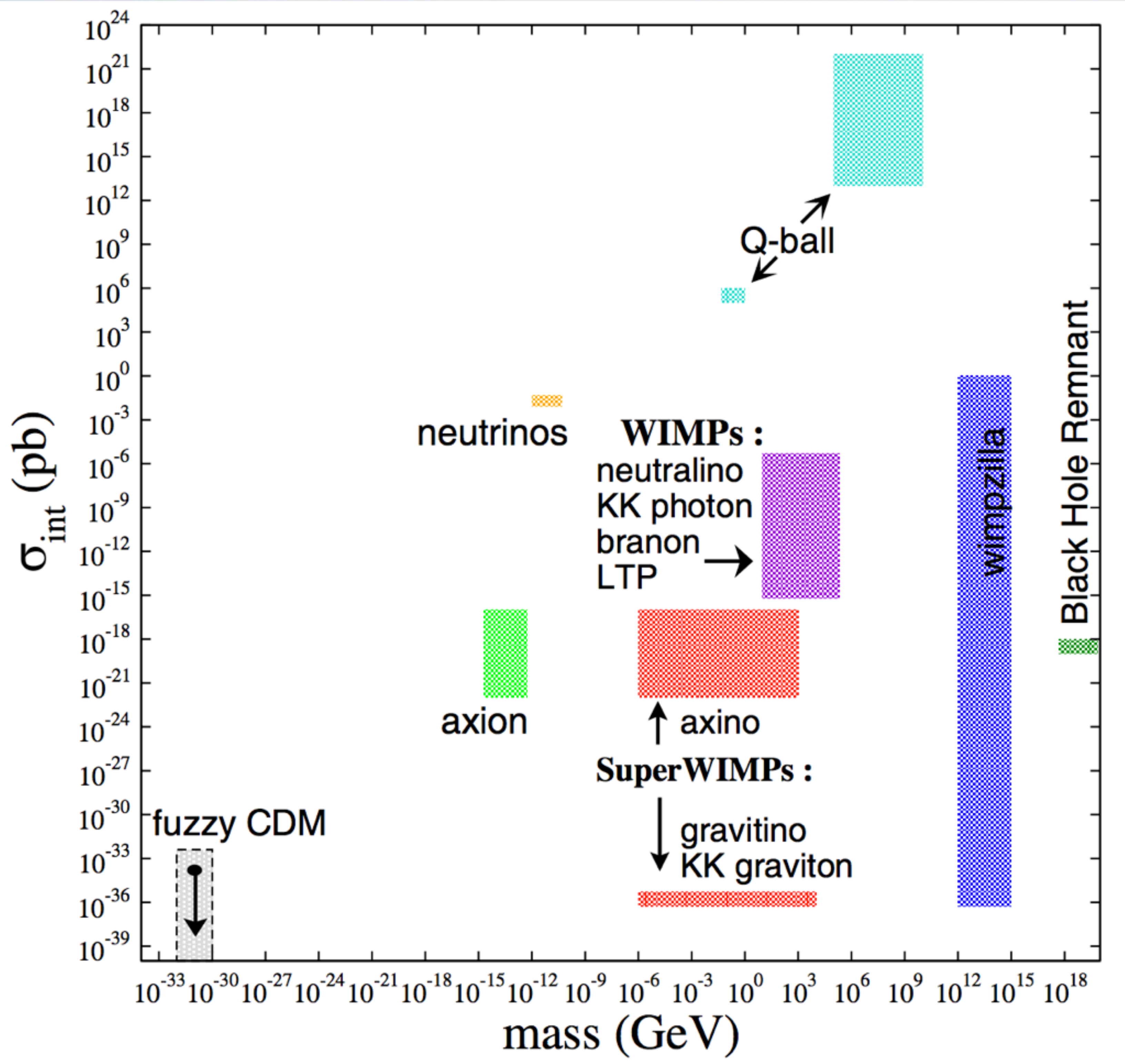
CP^3 Origins
Cosmology & Particle Physics

Based on:

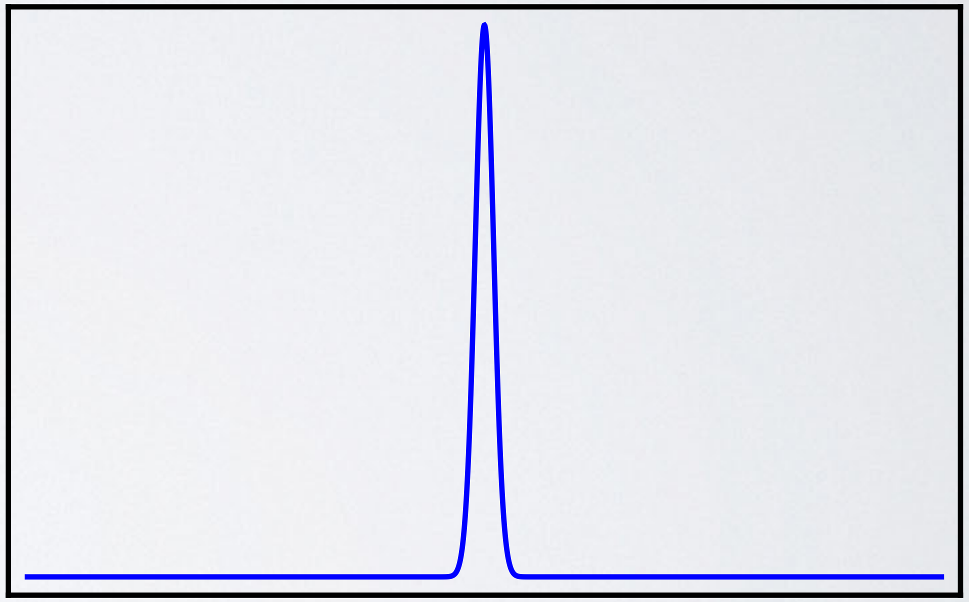
[1] J Cherry, M. Frandsen, and IMS, *Phys. Rev. Lett*. 114, 231303 (2015),arXiv: 1501.03166.
[2] A. Friedland, M. Graesser, IMS, L. Vecchi, *Phys. Lett.* B. (2012).
[3] D. Buarque Franzosi, M. T. Frandsen, and IMS [1507.XXXX].

PRELIMINARY RESULTS!

A ZOO OF CANDIDATES



most theorists' prior

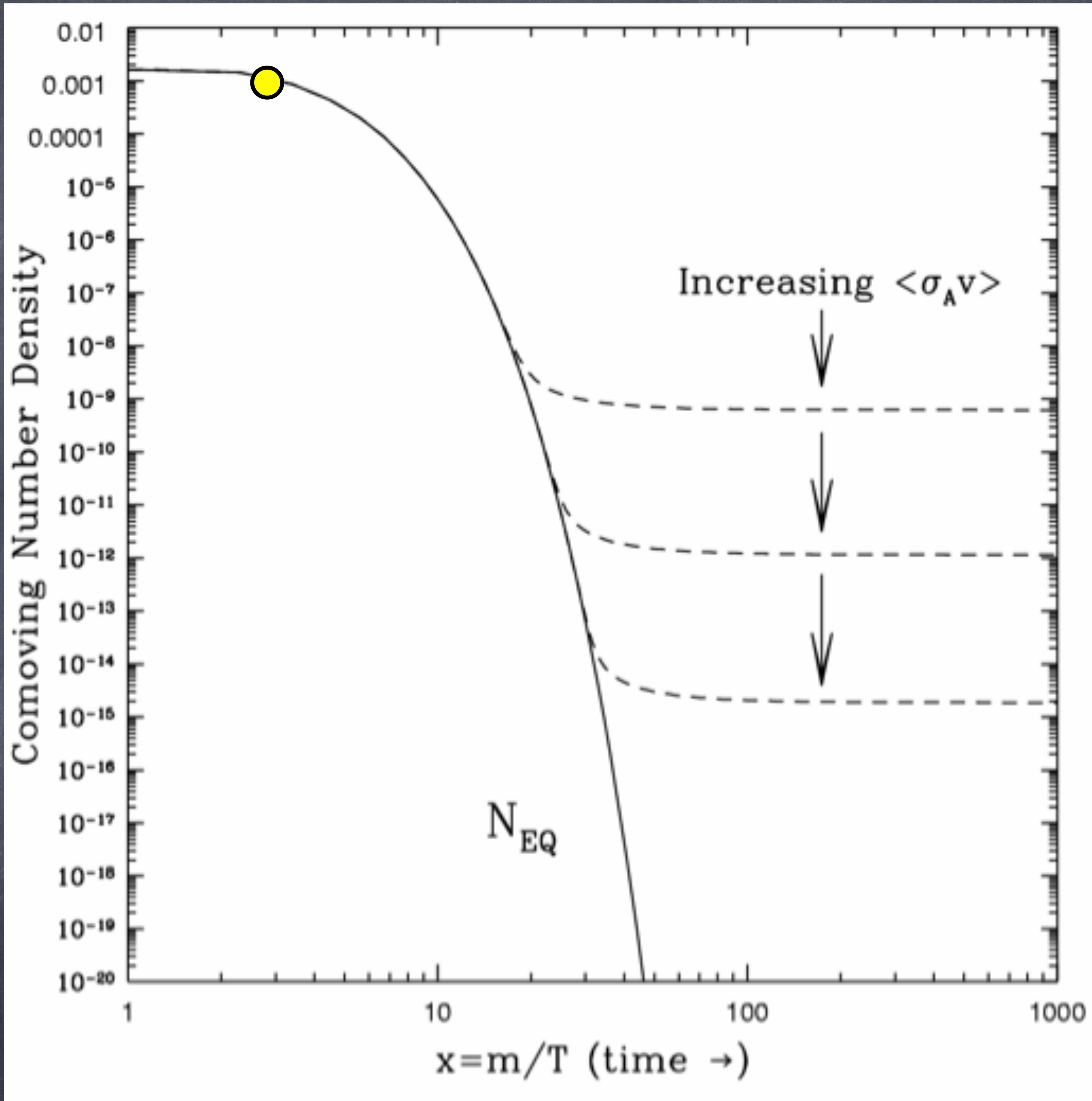


WIMP

Miracle WIMP

[Zel'dovich (1965), Zel'dovich, Okun, Pikelner (1965), Chiu (1966), Lee & Weinberg (1977), Wolfram (1979)]

- At early times, X is in thermal/chemical eq. via $X\overline{X} \leftrightarrow l\bar{l}$



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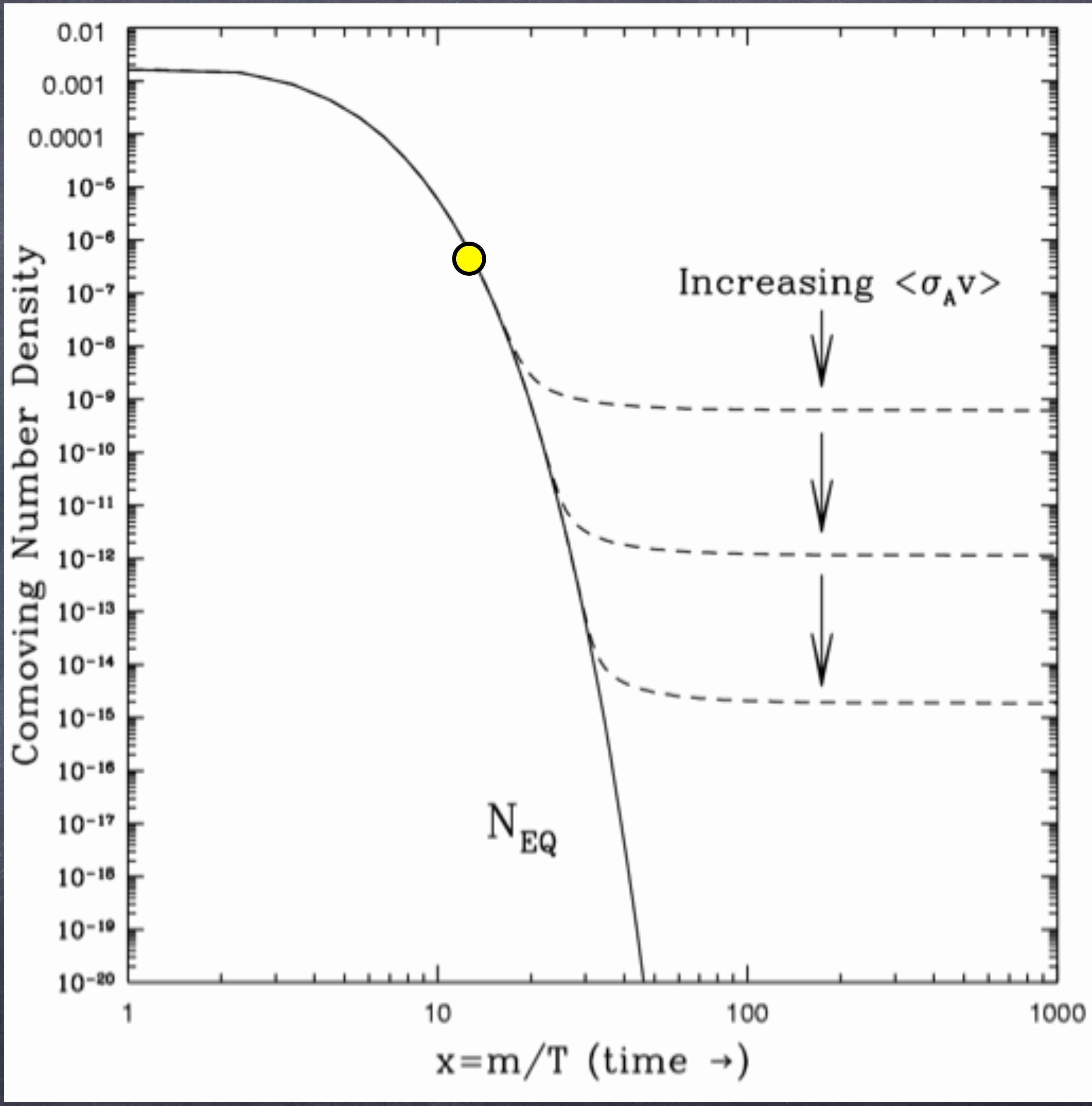
- The universe expands, and X's cool.



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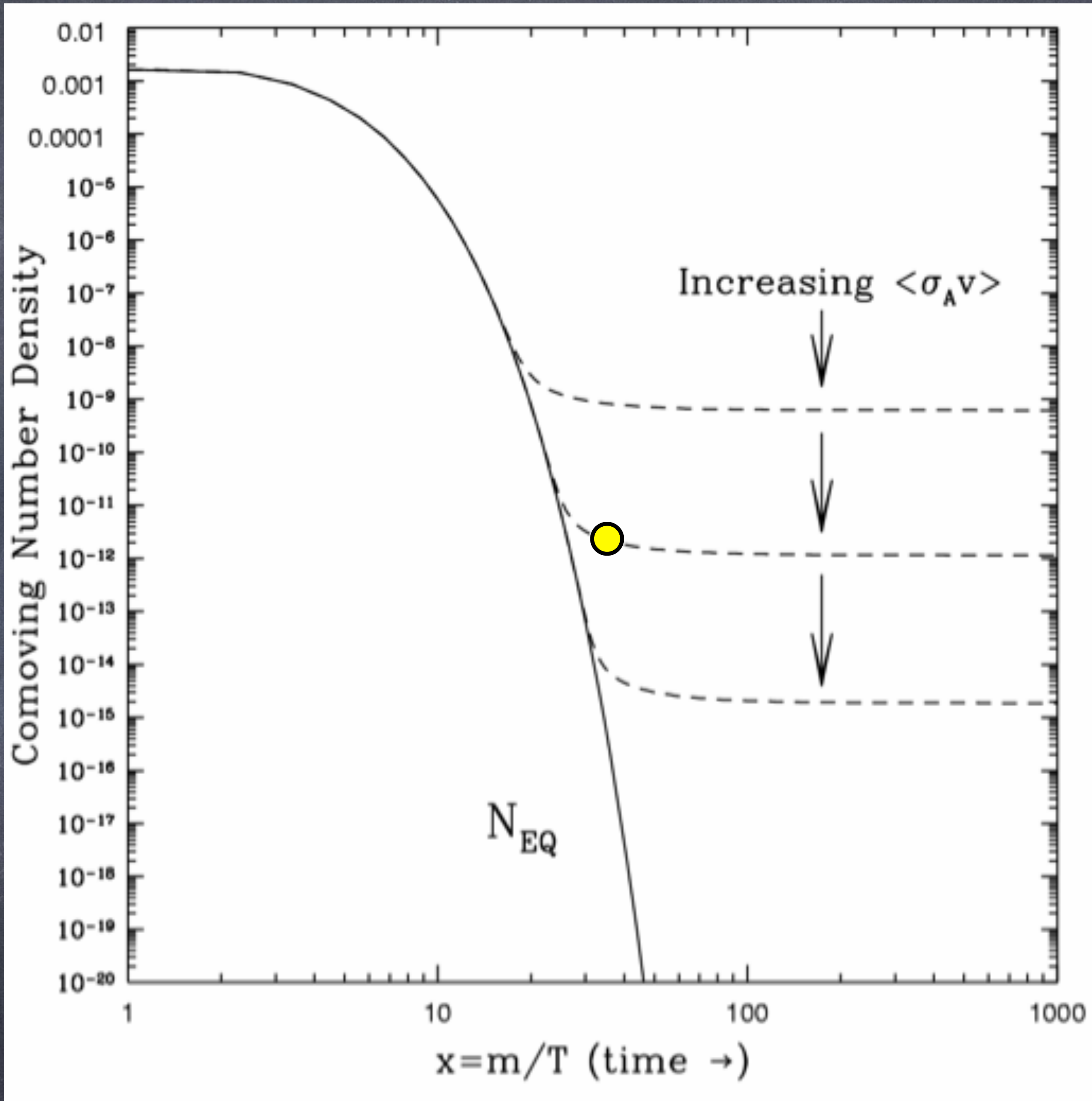
- At early times, X is in thermal/chemical eq. via $X\overline{X} \leftrightarrow l\bar{l}$
- The universe expands, and X's cool.
- Annihilations "freeze out" around:

$$H \sim \Gamma_{ann} \sim \langle \sigma v \rangle n_{eq}$$



$$\Omega_{DM} h^2 \sim 0.11 \left(\frac{3 \times 10^{-26} \text{ cm}^3/s}{\langle \sigma v \rangle} \right)$$

Miracle cross section

$$\Omega_{DM} h^2 \sim 0.2 \left(\frac{3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle} \right)$$

i) heavy WIMP: $(m_X \gg m_\phi)$

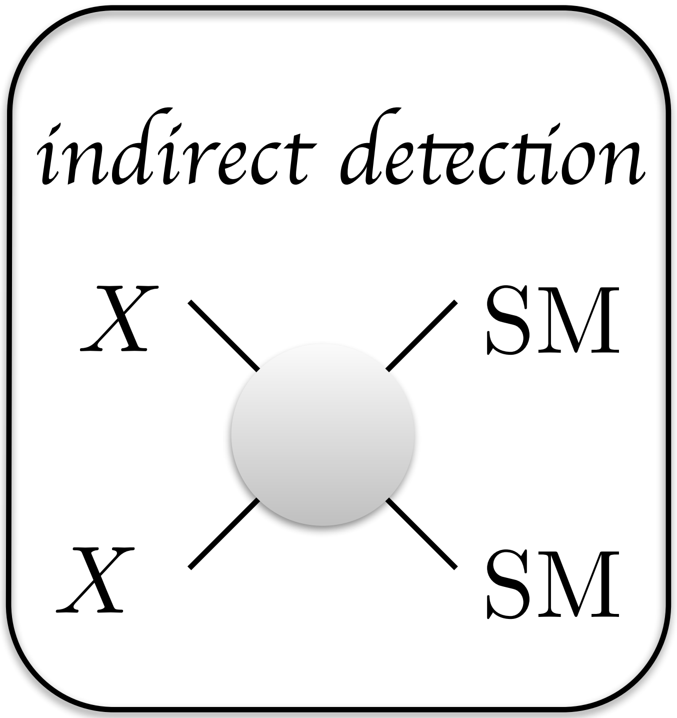
$$\langle \sigma v \rangle \sim \frac{1}{16\pi} \frac{g^4}{m_X^2} \quad \Rightarrow m_X \sim 1.2 \text{ TeV}$$

ii) light WIMP: $(m_X \ll m_\phi)$

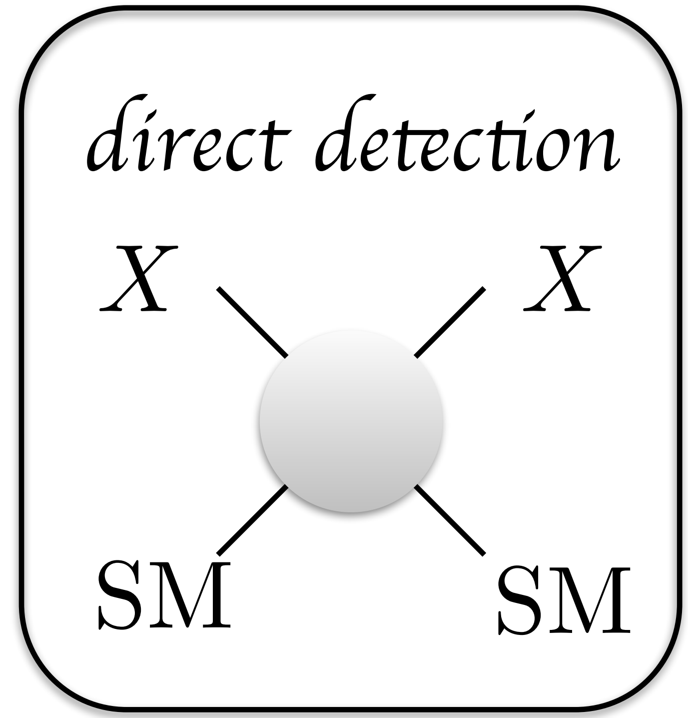
$$\langle \sigma v \rangle \sim \frac{1}{\pi} \frac{g^4 m_X^2}{m_\phi^4} \quad \overset{m_\phi \sim \text{TeV}}{\Longrightarrow} \quad m_X \sim 200 \text{ GeV}$$

More generally a "WIMPless" miracle
[Feng & Kumar (2008)]

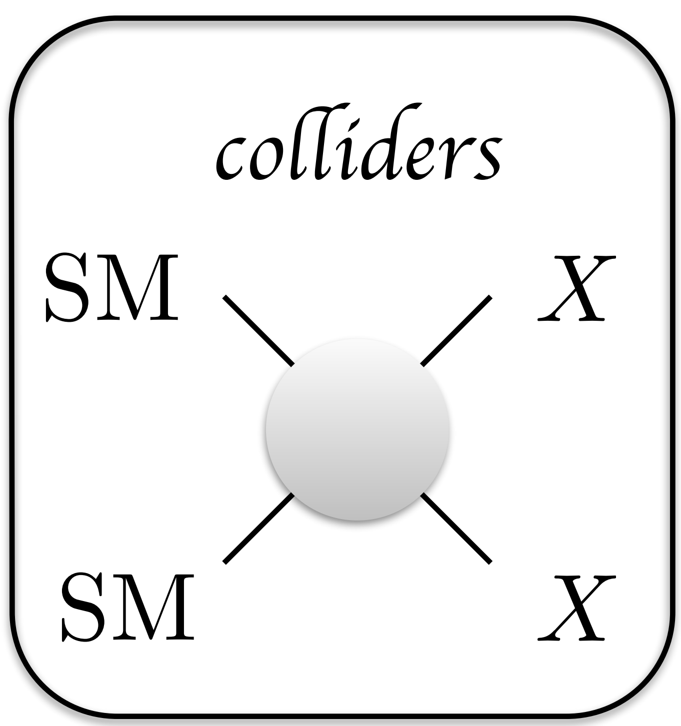
The Era of a lack of Data for Thermal Relics ???

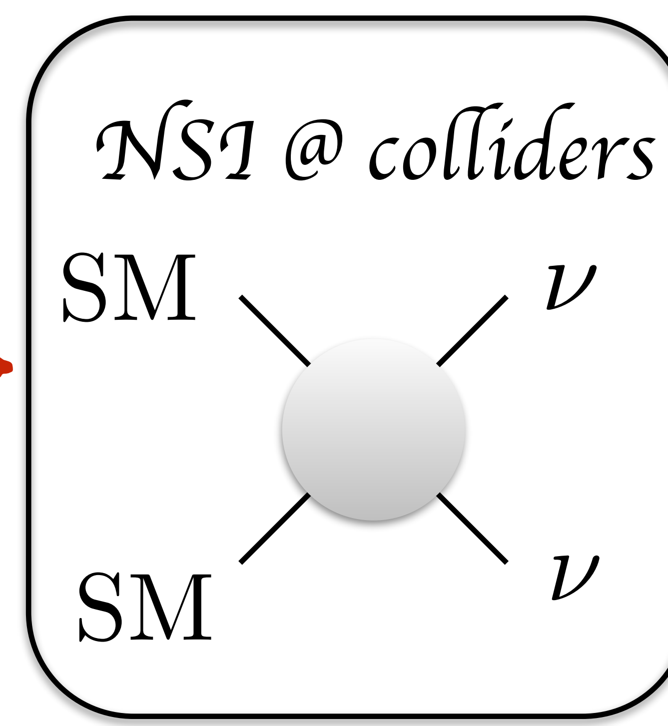


PART I:
Direct Detection
of DM annihilation

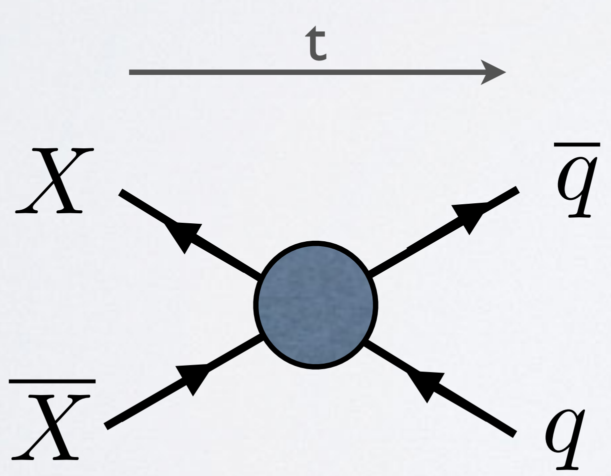


PART II:
Breaking the DM-nu
degeneracy at colliders.





PART 1: ON THE DIRECT DETECTION OF DARK MATTER ANNIHILATION

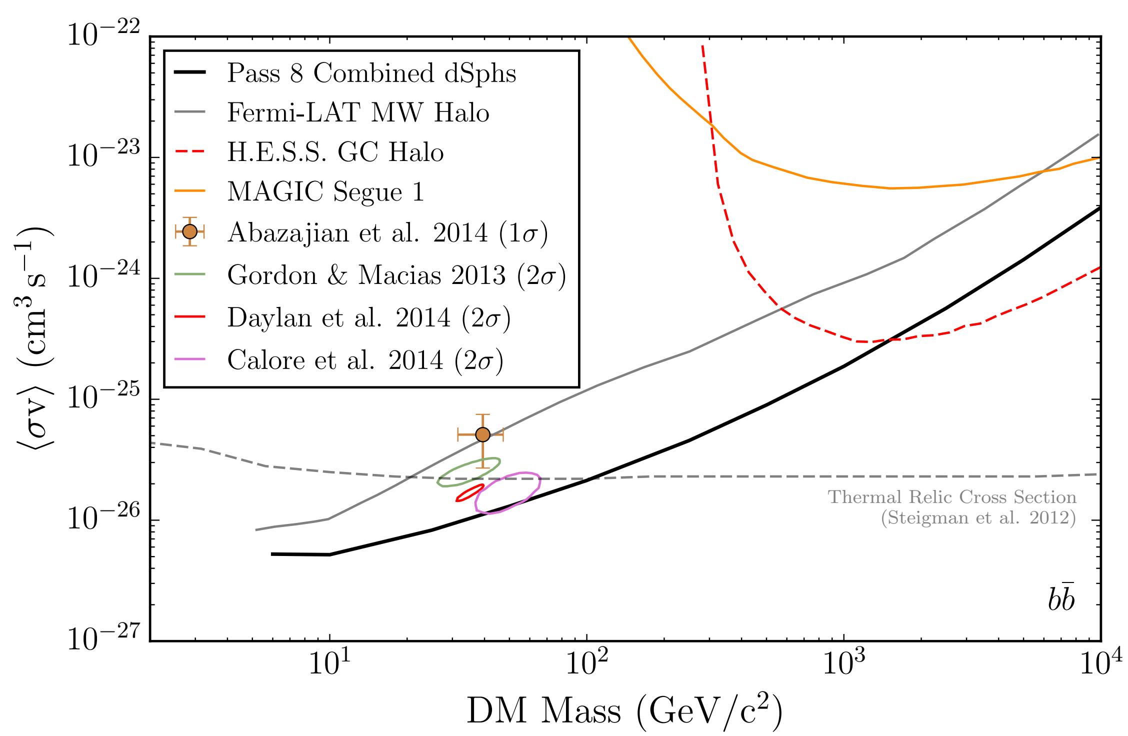


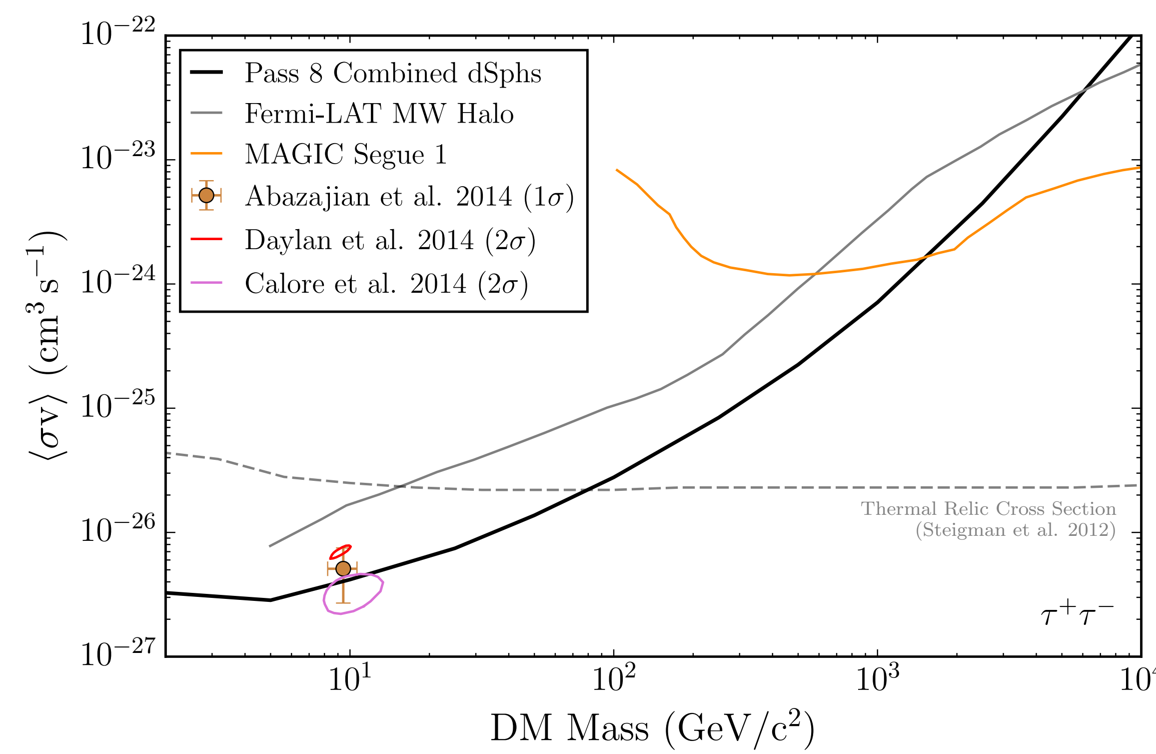
Based on:
John F. Cherry, Mads T. Frandsen, and IMS, Phys. Rev. Lett. 114, 231303 (2015), arXiv: 1501.03166.

Traditional tests of DM annihilation wiping out WIMPs

[1503.02641]

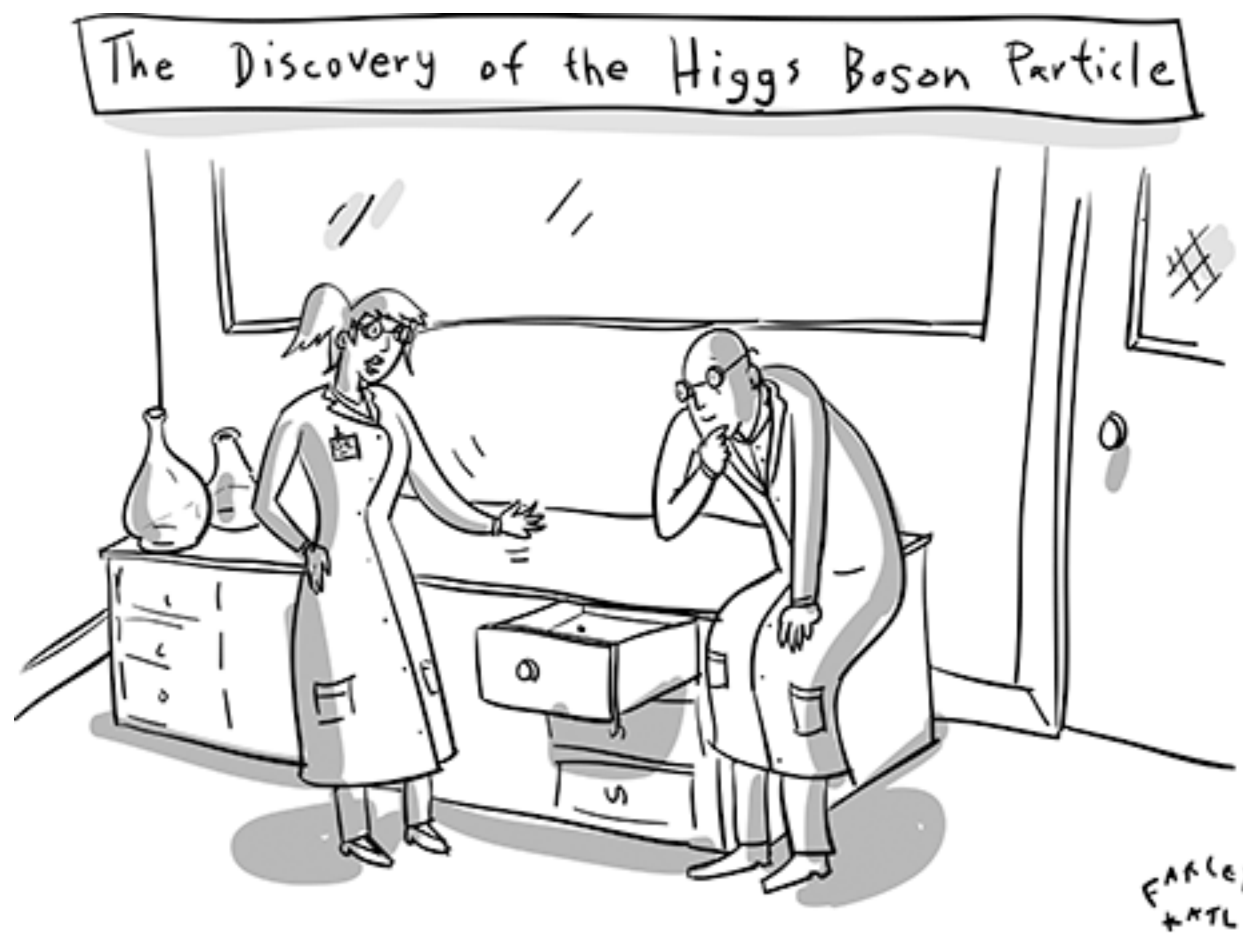
6 yr. Fermi-LAT data from combined analysis of 15 dSphs.





looks like WIMPs < 100 GeV ruled out.

Important to keep an open mind



"Always the last place you look!"

An alternative thermal relic

- Perhaps DM doesn't share tree-level interactions with the SM, but the products of its annihilation do.
- Call the DM annihilation products Y. The relic abundance of DM is set by

$$\overline{X}X \leftrightarrow \overline{Y}Y$$

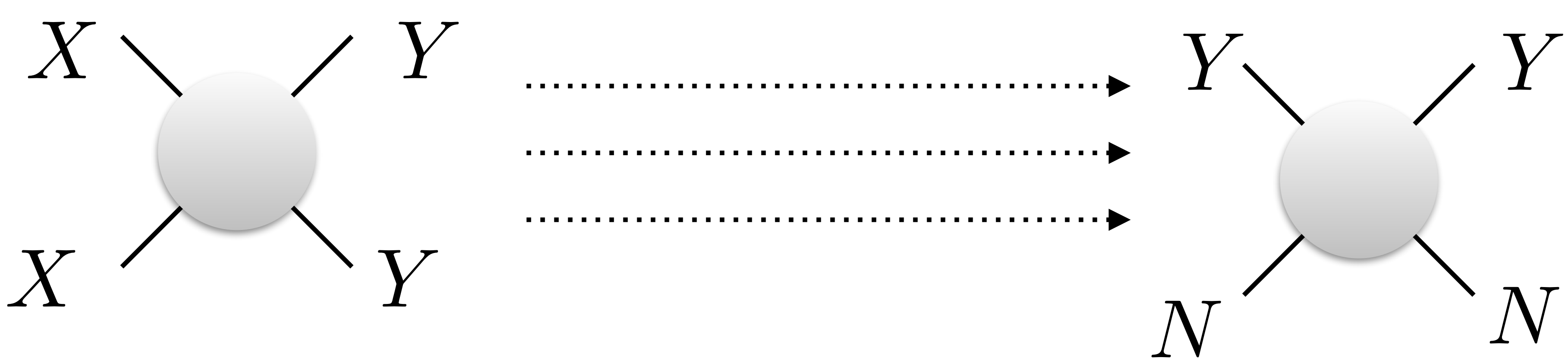
- For simplicity assume that Y is much lighter than X.
    - Y is *relativistic.*

See also: Huang, Zhao [1312.0011]
Agashe, Cui, Necib, Thaler [1405.7370]

Direct Probe of Annihilation

DM annihilation
in Galactic Center

LUX



$$\frac{dR}{dE_R} = \frac{\Phi_Y}{m_N} \int_{E_{min}(E_R)}^{\infty} dE_Y \frac{dN}{dE_Y} \left(\frac{d\sigma_{YN}}{dE_R} \right)$$

model-dependent

$$E_{min}(E_R) \quad = \quad \sqrt{m_N E_R / 2}$$

thanks to relativistic kinematics.

Local flux of Y's:

$$\Phi_Y \quad = \quad 1.6 \ \times 10^{-2} \mathrm{cm}^{-2} \mathrm{s}^{-1} \left(\frac{\langle \sigma_{\bar{X} X \to \bar{Y} Y} v_{rel} \rangle}{5 \times 10^{-26} \ \mathrm{cm}^3 \mathrm{s}^{-1}} \right) \left(\frac{20 \ \mathrm{MeV}}{m_X} \right)^2$$

Results from LUX data

- Most obvious case for Y: a SM neutrino.
- Need stronger than EW scale interactions to probe thermal relics.
- Well-studied model: Higgs portal implementation.

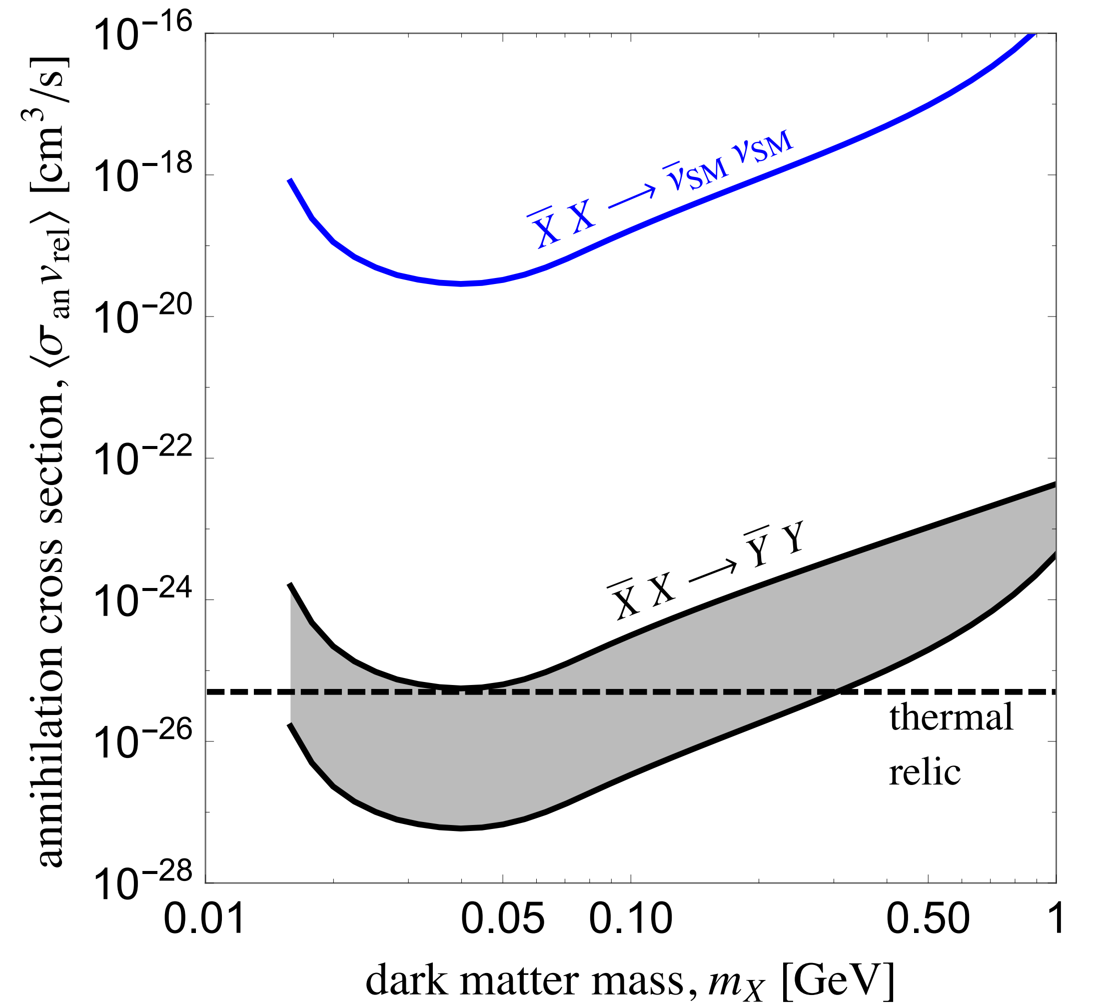
$$\mathscr{L} \supset b|\phi|^2|H|^2 + g\phi\overline{Y}Y$$

- For sufficiently heavy phi, interaction strength well-described by effective operator:

$$G_Y(\overline{N}N)(\overline{Y}Y)$$

- Invisible Higgs width constrains:

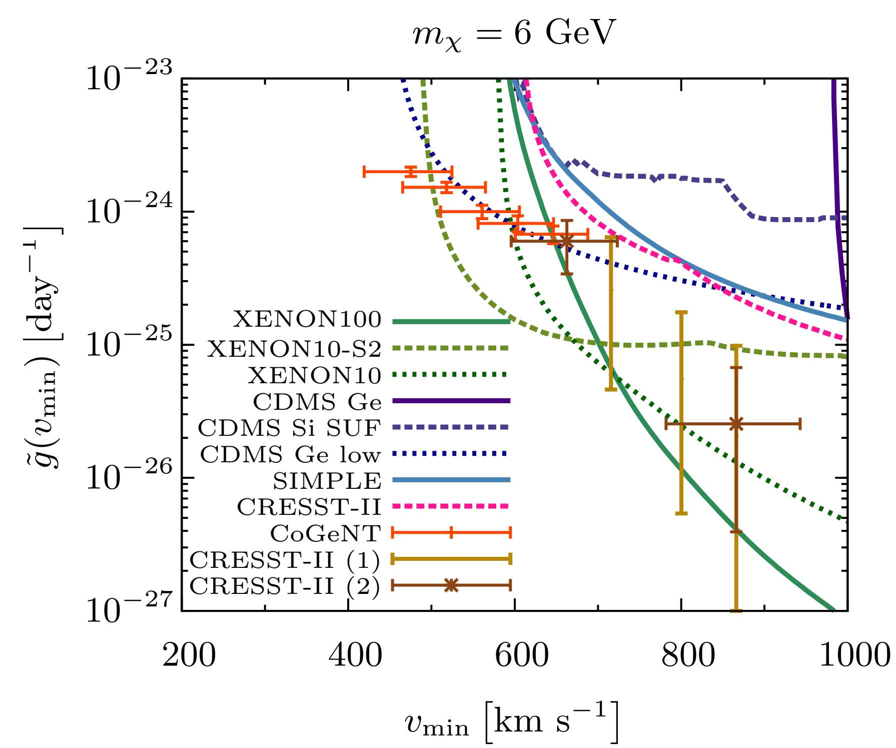
$$G_Y = \frac{(g\sin\theta)f_N}{m_\phi^2} \simeq 7\times 10^3\ G_F\ \left(\frac{g\sin\theta}{10^{-2}}\right)\left(\frac{0.2\ \mathrm{GeV}}{m_\phi}\right)^2$$



Lightning "review" of halo-independent methods

Fox, Liu, Weiner [1011.1915]

[1111.0292]



- For ordinary non-relativistic DM scattering:

$$\frac{dR}{dE_R} = \frac{\rho_{DM}\sigma_n}{2m_X\mu_{nX}^2}A^2F^2(E_R)\int_{v_{\min}(E_R)}^{\infty}\frac{f(v)}{v}d^3v$$

- Trade (m_X, σ_n) for $(v_{\min}, \tilde{g})$

where $\tilde{g}(v_{min}) \equiv \frac{\rho_{DM}\sigma_n}{m_X}\int_{v_{\min}(E_R)}^{\infty}\frac{f(v)}{v}d^3v$

- How to construct g-vmin sensitivity plot:

(1) For ***signals:*** $\tilde{g}(v_{\min}) \equiv 2\mu_n^2(A^2F^2(E_R))^{-1}dR/dE_R,$

(2) For ***constraints***:

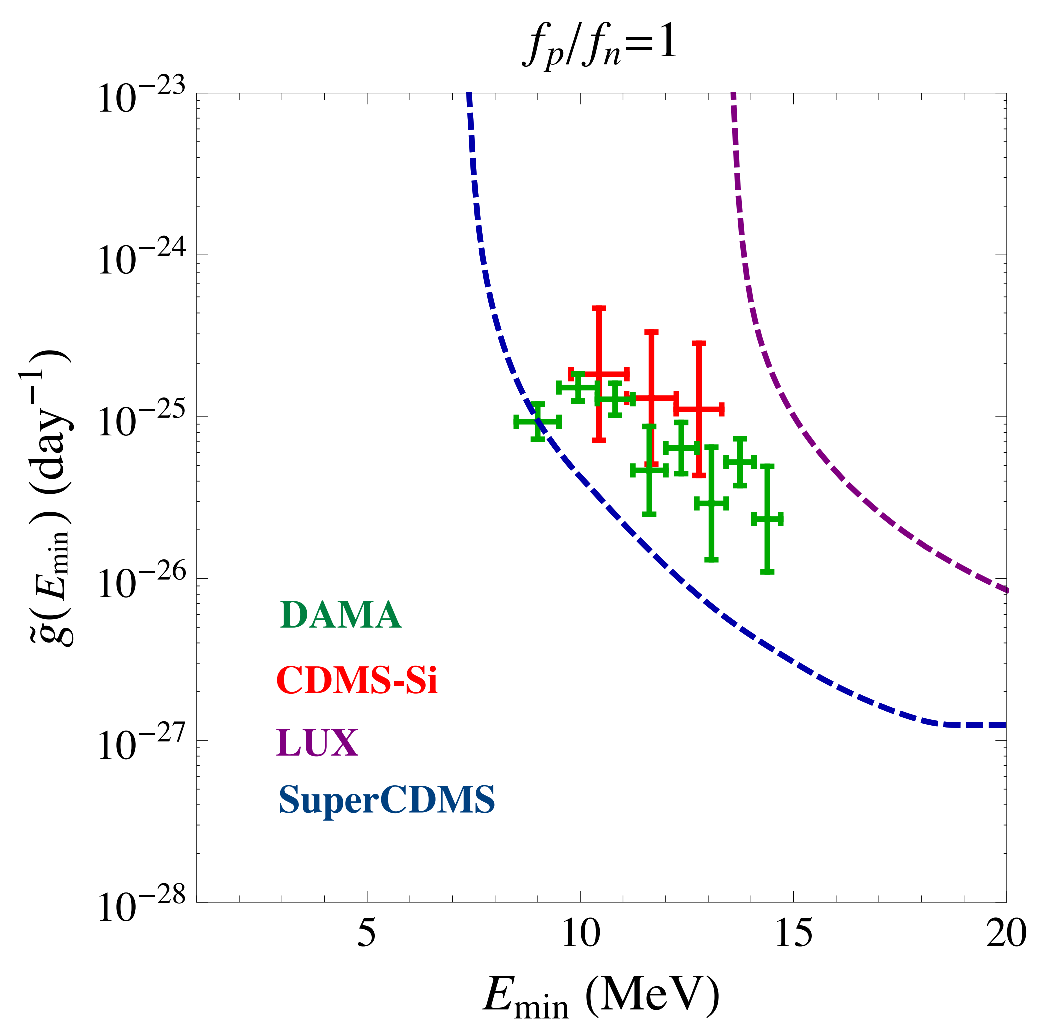
Use $f(v) \geq 0$ which implies, $\boxed{\tilde{g}(v_{\min}) \geq \tilde{g}(\hat{v}_{\min})\,\Theta(\hat{v}_{\min} - v_{\min})}$

At any given vmin pt.,most conservative constraint on velocity integral comes from a step function.

Generalization to relativistic scattering

Apply same "isospin-conserving" assumption:

$$\tilde{g}(E_{\min}) \equiv 2\mu_n^2 (A^2 F^2(E_R))^{-1} dR/dE_R,$$



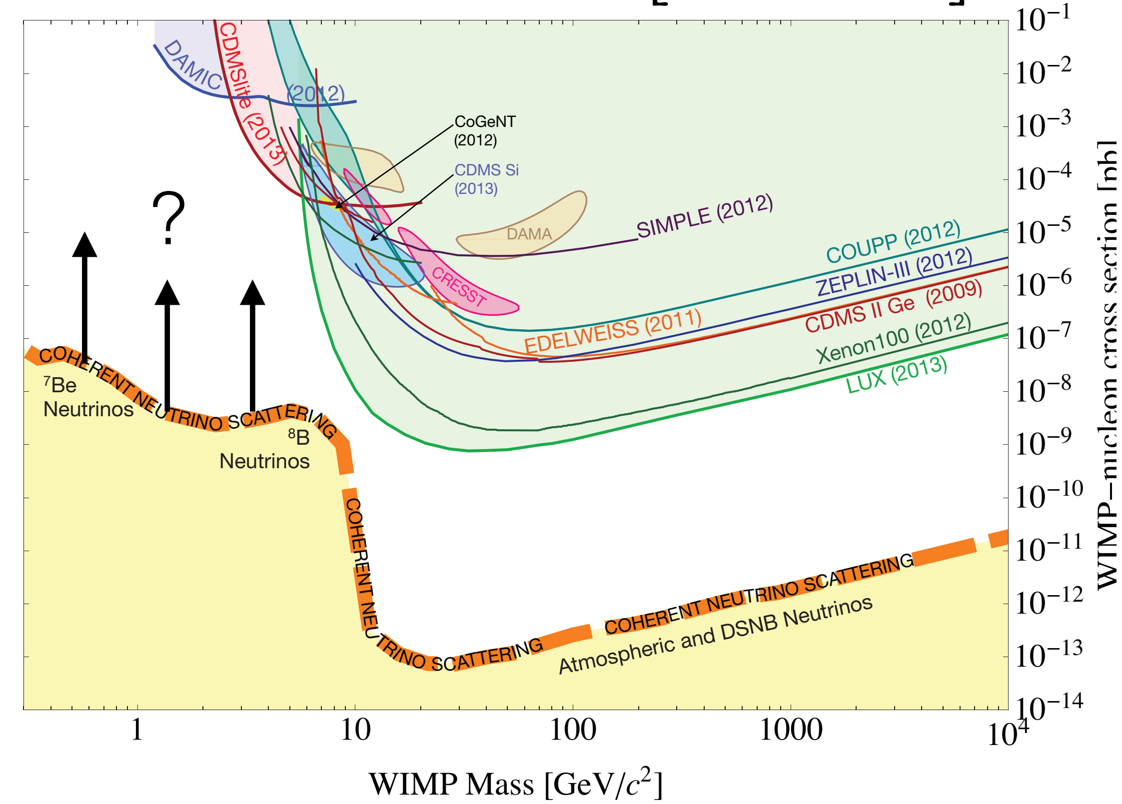
Discussion of results:

- f(v) does not enter.
- No dependence on the DM density distribution.
- No dependence on the assumed form of the Y-nucleus scattering, Y energy spectrum.
- ***This result applies to all DM masses.***

- **Applies equally well to non-DM direct detection possibilities…**

Neutrino “backgrounds”

[1307.5458]



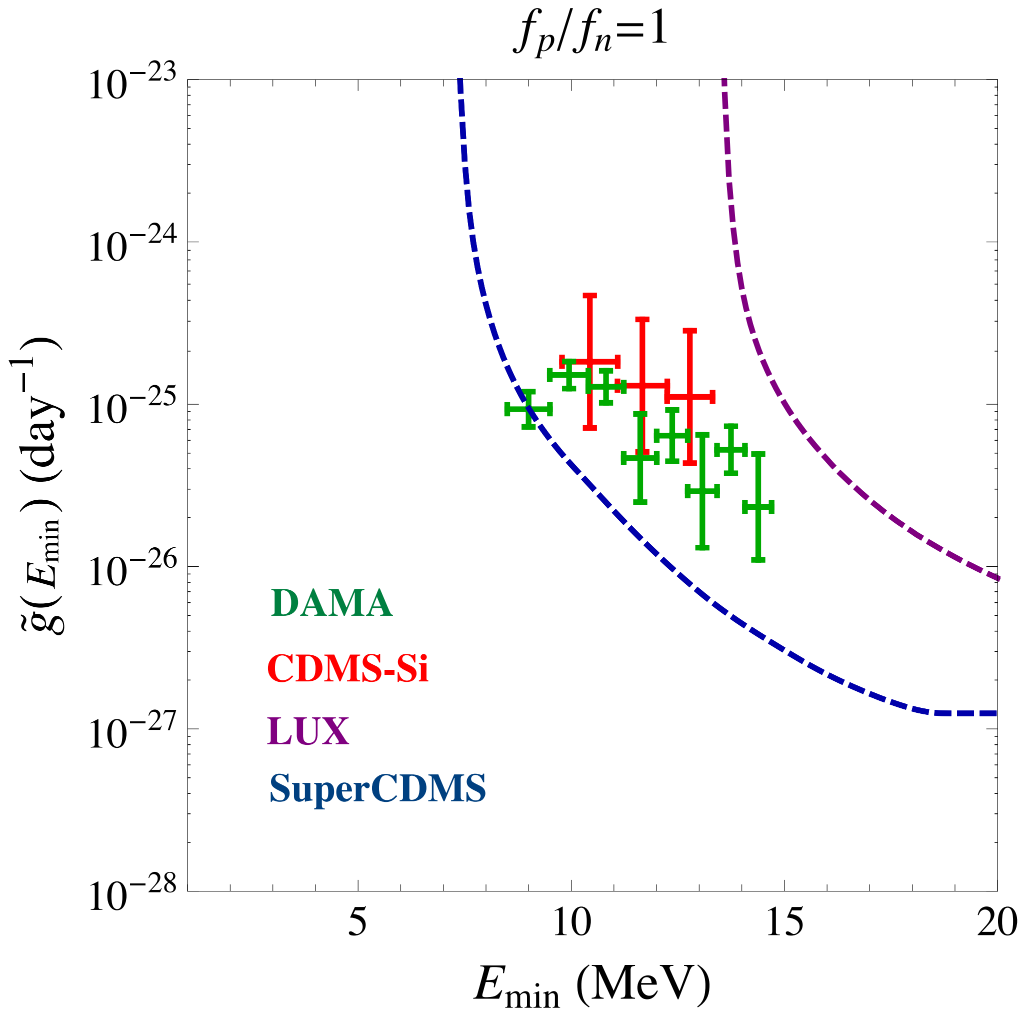
- Solar neutrinos will eventually be a direct detection background.
- If neutrinos have new interactions, that signal might be closer than expected, see e.g. Pospelov (1103.3261), Pospelov, Pradler (1203.0545), Kopp, Harnik, Machado (1202.6073).
- Can annually modulate with appropriate mass splittings:

$$l_{\rm osc} \sim {\rm AU} \left(\frac{E}{10\ {\rm MeV}}\right) \left(\frac{10^{-10}\ {\rm eV}^2}{\Delta m^2}\right)$$

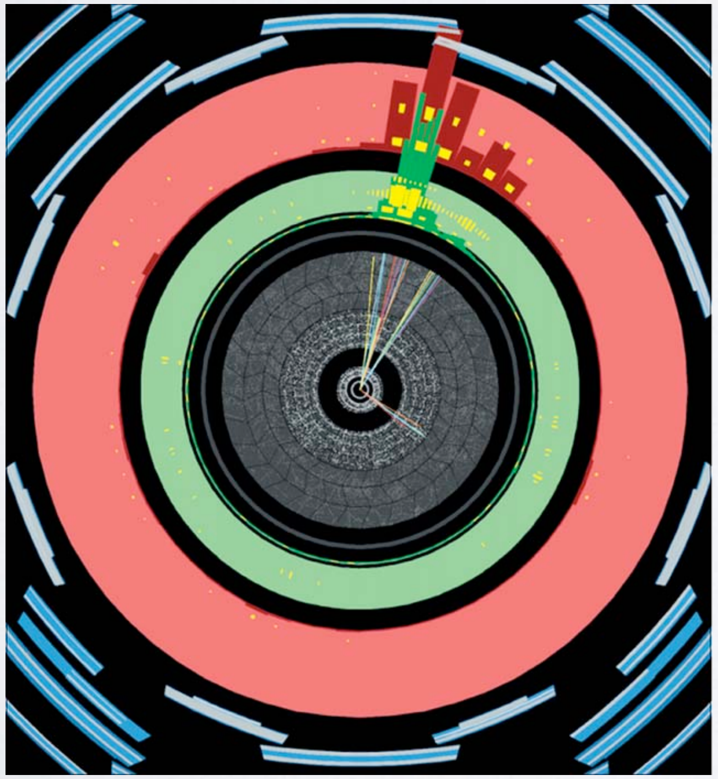
- ***SuperCDMS now rule out this explanation for DAMA/CDMS-Si.***

Review of Part I

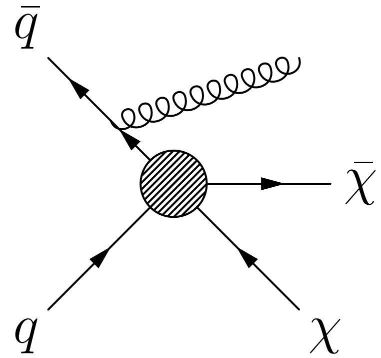
- Test thermal relics in a new way & gives direct detection access to < GeV DM.
- DM can annihilate to light states that do the scattering at direct detection experiments.
- Novel phenomenology distinct from other DM exotica e.g. inelastic, isospin-violating, etc.
- Isn't covered in the "model-independent" non-relativistic eff. operator framework of Fitzpatrick et al. [1203.3542], [1211.2818].



PART II:
NEW OR ν MISSING ENERGY AT THE LHC?



Based on:
- Graesser, Friedland, IMS, Vecchi, Phys.Lett. B714 (2012) 267-275, arXiv: 1111.5331.
- Buarque Franzosi, Frandsen, IMS [1507.XXXX]



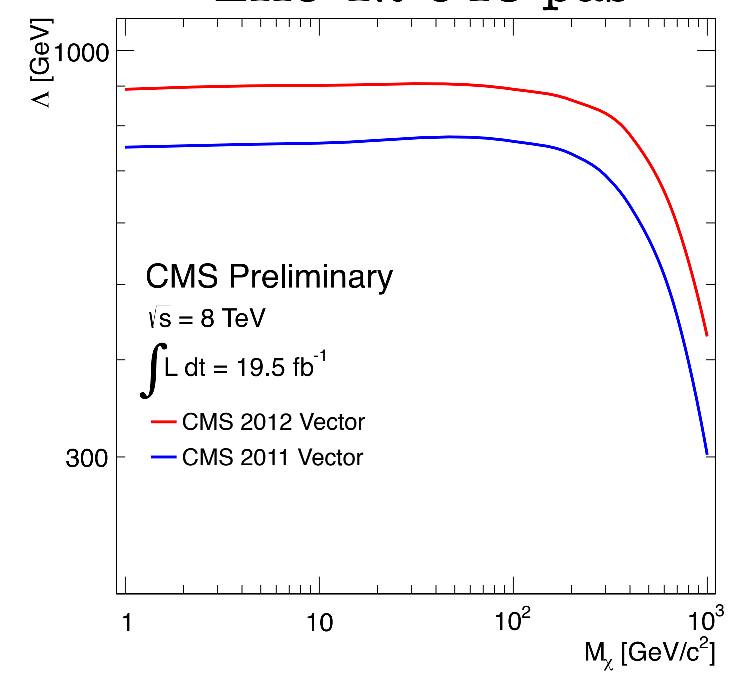
The DM monojet industry

- Take an interaction: $\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$
- Use LHC data to constrain cutoff scale.
- Put limits on DM-nucleon cross section to compare against direct searches.
- Huge amount of work in last few years, expanding to mono-X searches, etc.

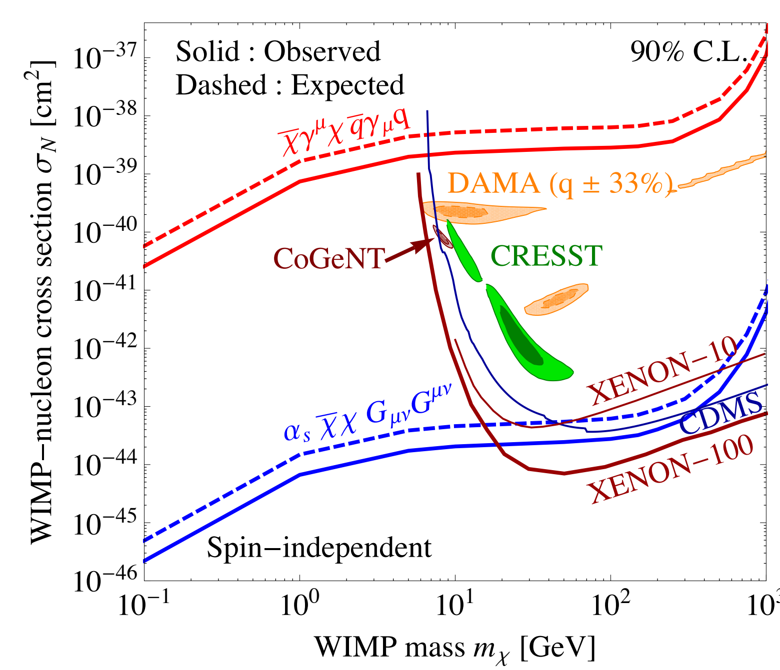
hep-ph/0403004, 0912.4511, 1002.4137, 1005.3797, 1107.2666 ,1109.4398, 1111.5331, 1112.5457,1202.2894 , 1203.1662 , 1204.0821 , 1204.3839, 1208.4605 , 1209.0231, 1211.6390, 1302.3619, 1307.2253, 1308.0592 , 1308.6799 , 1402.1275 , 1407.8257, 1409.2893, 1502.05721, 1503.05916, 1503.07874, …

- ***Now a standard search carried out by CMS & ATLAS.***

EXO-12-048-pas



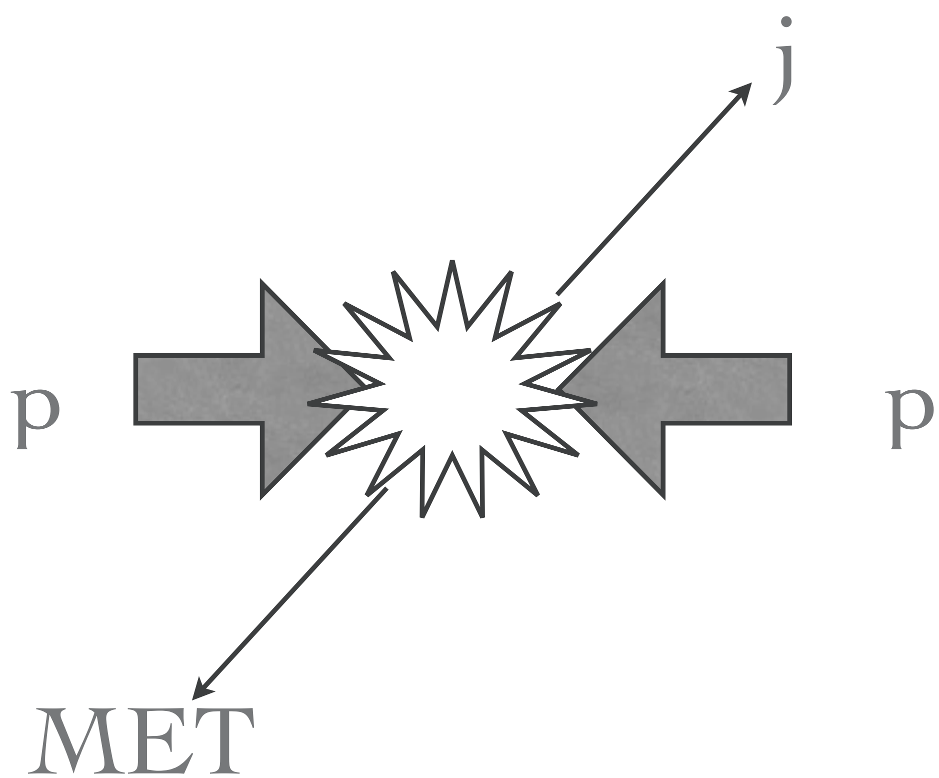
ATLAS 7TeV, 1fb^{-1} VeryHighPt



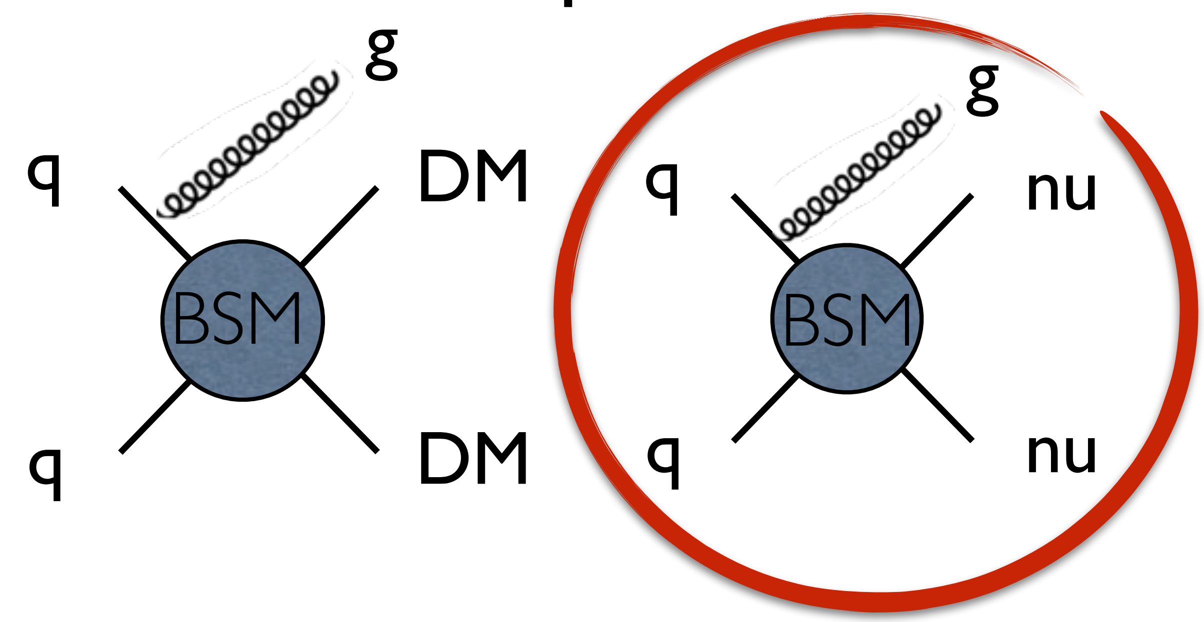
What to do with missing energy signals*?

* = assuming they appear in future data.

A point in LHC space



Many points in theory space



etc...

Only confirmed source of missing energy are neutrinos.
Conservative to start with the neutrino hypothesis first.

DM can be inferred at the LHC *if*
the neutrino hypothesis is rejected.

How strong can neutrino-proton interactions be?

Simple parameterization of nu-proton interactions: EFT

- First consider dimension-5 interactions, e.g. magnetic moment:

$$\mathscr{L} \supset \mu_\nu F^{\mu\nu} \overline{\nu} \sigma_{\mu\nu} \nu,$$

- Strongest constraints come from the Kalinin Nuclear Power Plant with the GEMMA spectrometer:

$$\mu_\nu < 3.2 \times 10^{-11} \; \mu_B$$

[Beda et al., 1005.2736]

- However, the LHC sensitivity can be inferred from the DM literature in the “light DM” limit:

$$\mu_\nu \lesssim 3 \times 10^{-5} \; \mu_B$$

[Barger, Keung, Marfatia, Tseng, 1206.0640]

→ Neutrino magnetic moments won’t produce much missing energy at the LHC.

Dim-6 Operators: Generalizing Fermi

PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

L. Wolfenstein
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

Non-standard neutrino interactions (NSIs):

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\, \epsilon^{fP}_{\alpha\beta}(\overline{\nu}_\alpha\gamma^\rho\nu_\beta)(\overline{f}\gamma_\rho P f)$$

What about SU(2)?

To avoid stringent bounds on charged leptons, insert some Higgs VEVs on a dim-8 operator:

$$\mathcal{L}_{\mathrm{NSI}}^{\mathrm{dim}-8} = -\frac{4\epsilon_{\alpha\beta}^{qP}}{v^4}(\overline{HL_\alpha}\gamma^\mu HL_\beta)(\overline{q}\gamma_\mu Pq)$$

$$\to -2\sqrt{2}\,G_F\,\epsilon_{\alpha\beta}^{qP}\,(\overline{\nu}_\alpha\gamma^\mu\nu_\beta)\,(\overline{q}\gamma_\mu Pq)\left(1+\frac{h}{v}\right)^2$$

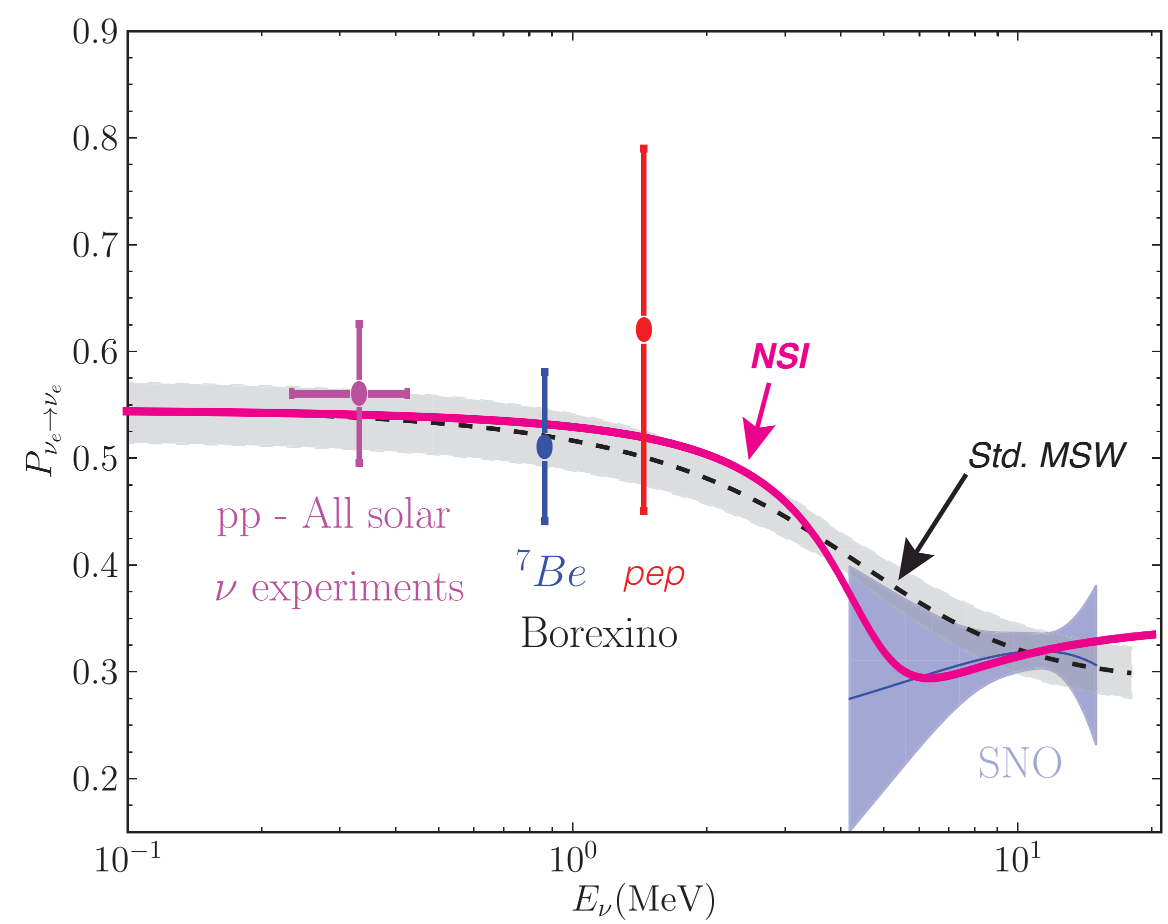
Berezhiani, Rossi [hep-ph/0111137]

Proof of principle model with these features:
See Pospelov's "baryonic neutrino" [1103.3261] with a Z' coupling to neutrinos and baryons.

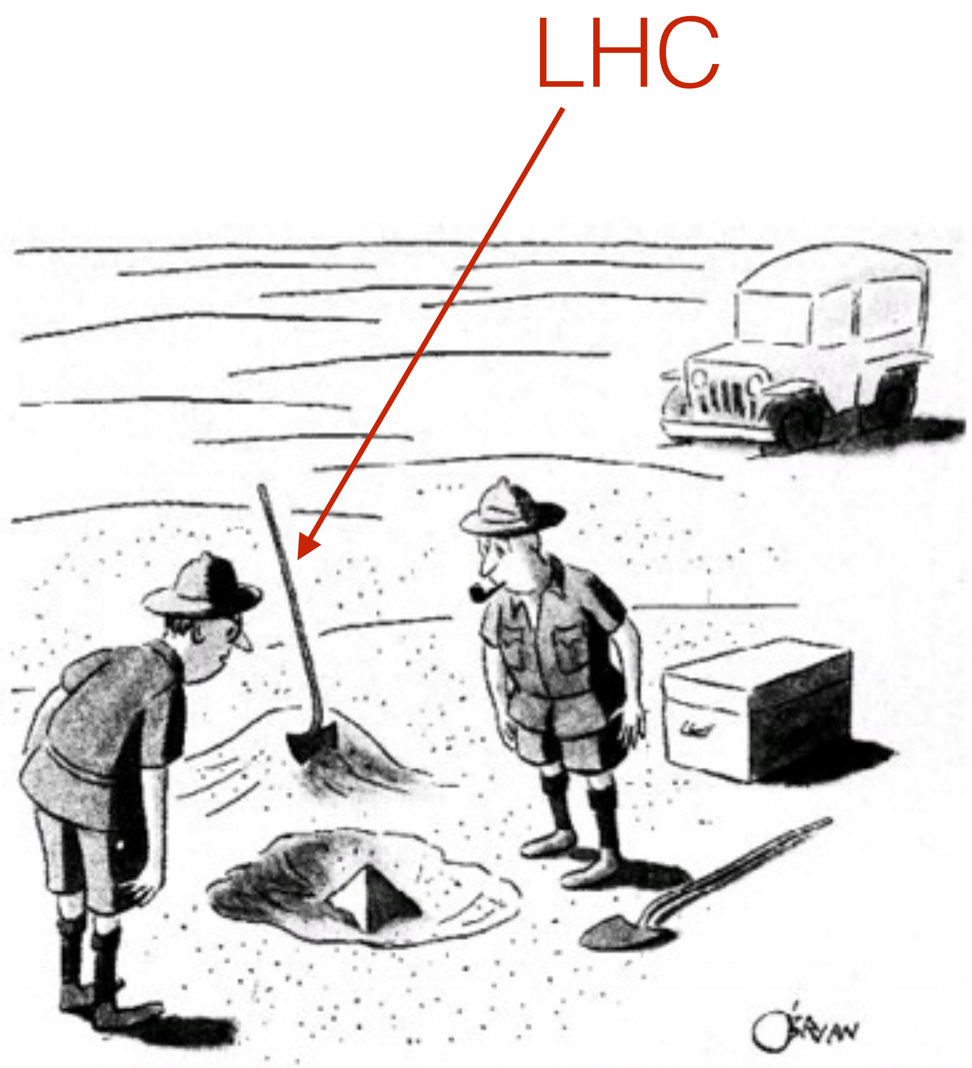
Additional motivation from the Sun

- Maximally minimal setup: just one NSI term nonzero, $\varepsilon_{e\tau}$
- Predicted MSW "upturn" so far unseen.
- NSI provides a better fit.
- Just below present CHARM limit (< 0.5).

$$\varepsilon_{e\tau} = 0.4$$



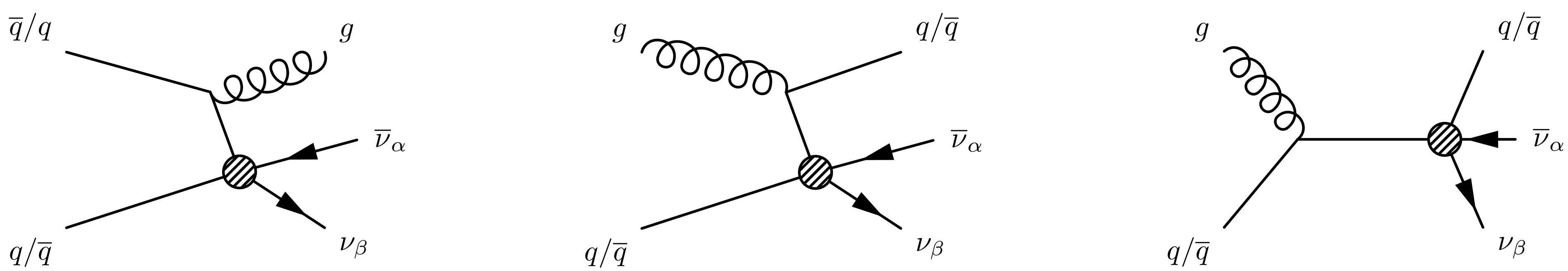
A. Friedland, IMS [1207.6642]



“This could be the discovery of the century. Depending, of course, on how far down it goes.”

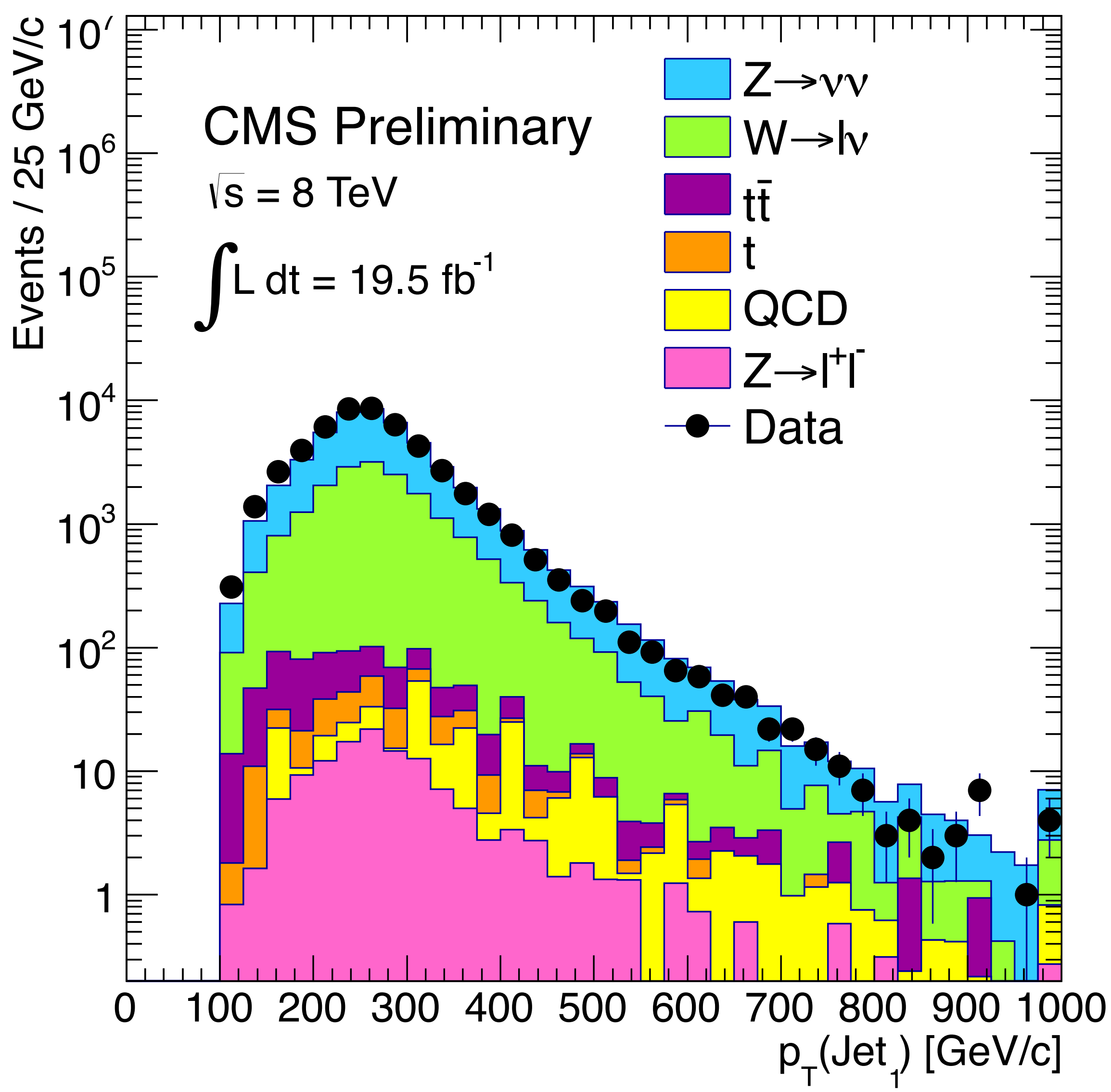
Multipurpose Monojets: not just for DM anymore

$$pp/p\overline{p} \rightarrow j + \mathrm{MET}$$

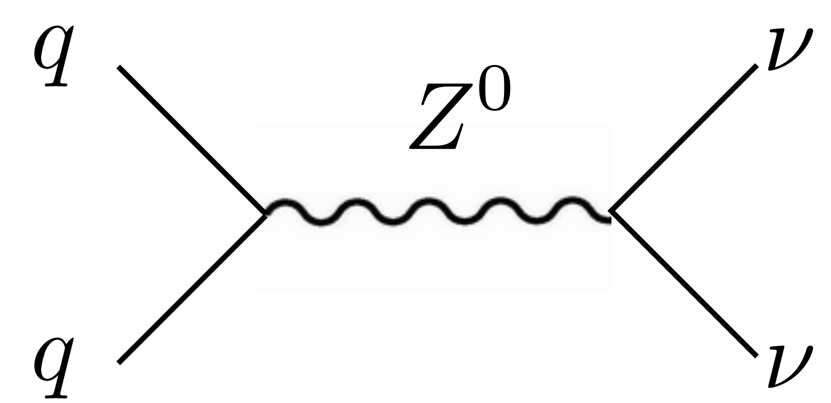


First consider the case where the interaction is contact.

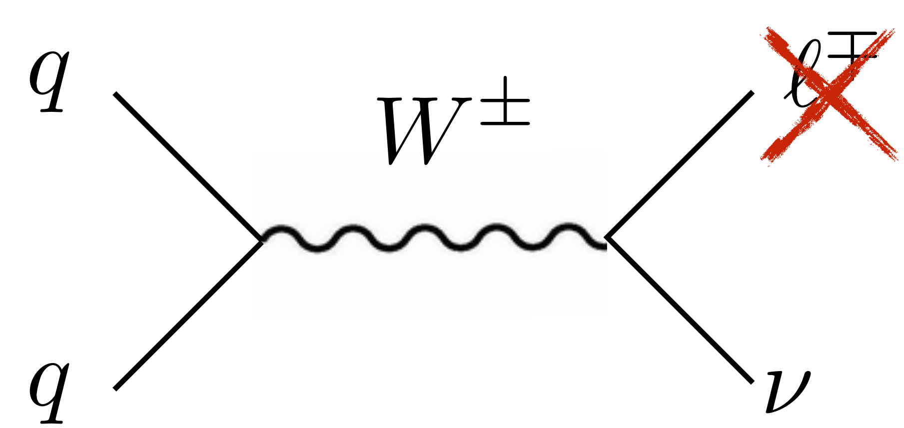
Monojet Backgrounds



Real monojets:



Fake monojets:



missed low-E or longitudinal lepton.

Zeroth Order: cut and count limit

Madgraph for parton-level signal.

Pythia for hadronization/showering.

Bounds obtained via simple counting experiment.

For example, ATLAS HighPT search obtained:

$$N_{obs} = 965$$

$$N_{\rm bkg} = 1010 \pm 37 \pm 65$$

$$N_{\rm BSM} < 192$$

$$@\ 95\%{\rm CL}$$

Contact NSI

$$\mathscr{L}_{NSI} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{fP}\left(\overline{\nu}_\alpha\gamma_\rho\nu_\beta\right)\left(\overline{f}\gamma^\rho P f\right)$$

$$@\ \sqrt{s} = 7\ \mathrm{TeV}$$

- Notice that LHC limits on u-quarks are stronger than for d-quarks thanks to PDFs.

- Subtlety: *flavor off-diagonal* constraints stronger because conjugate reaction is distinct.

$$pp \longrightarrow j\overline{\nu}_\alpha\nu_\beta$$

$$pp \rightarrow j\overline{\nu_\beta}\nu_\alpha$$

Sum two processes incoherently.

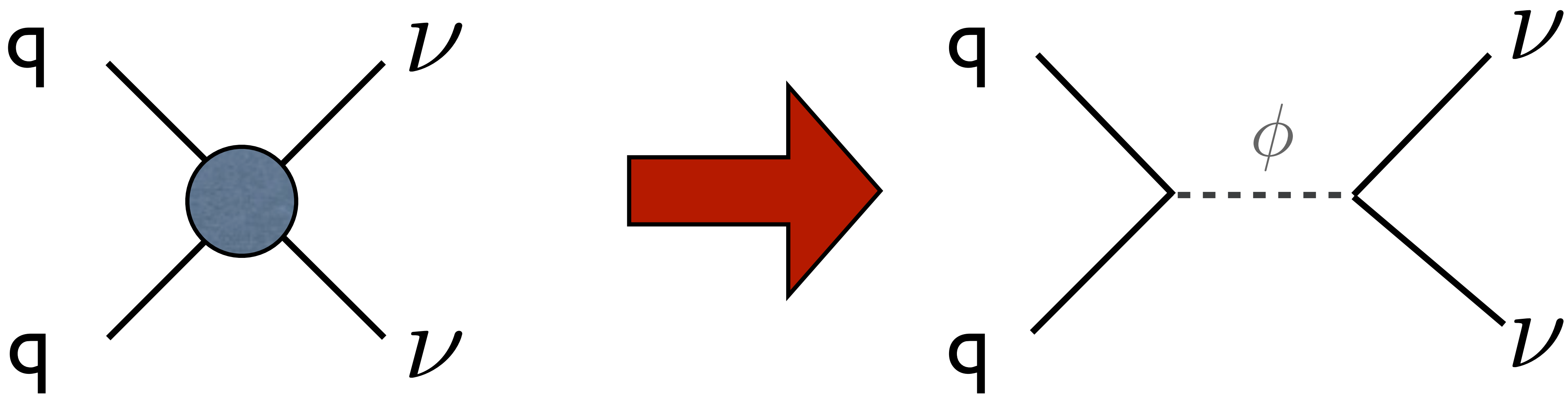
	CDF		ATLAS [31]		
	GSNP [32]	ADD [4, 5]	LowPt	HighPt	veryHighPt
$\varepsilon^{uP}_{\alpha\beta=\alpha}$	0.45	0.51	0.40	0.19	0.17
$\varepsilon^{dP}_{\alpha\beta=\alpha}$	1.12	1.43	0.54	0.28	0.26
$\varepsilon^{uP}_{\alpha\beta\neq\alpha}$	0.32	0.36	0.28	0.13	0.12
$\varepsilon^{dP}_{\alpha\beta\neq\alpha}$	0.79	1.00	0.38	0.20	0.18

Friedland, Graesser, IMS, Vecchi, [1111.5331]

→ *Already setting new limits stronger than low-energy constraints for some flavor-structures.*

E.g. LHC bests the CHARM limit on $\varepsilon_u^{ee}, \varepsilon_d^{ee}$

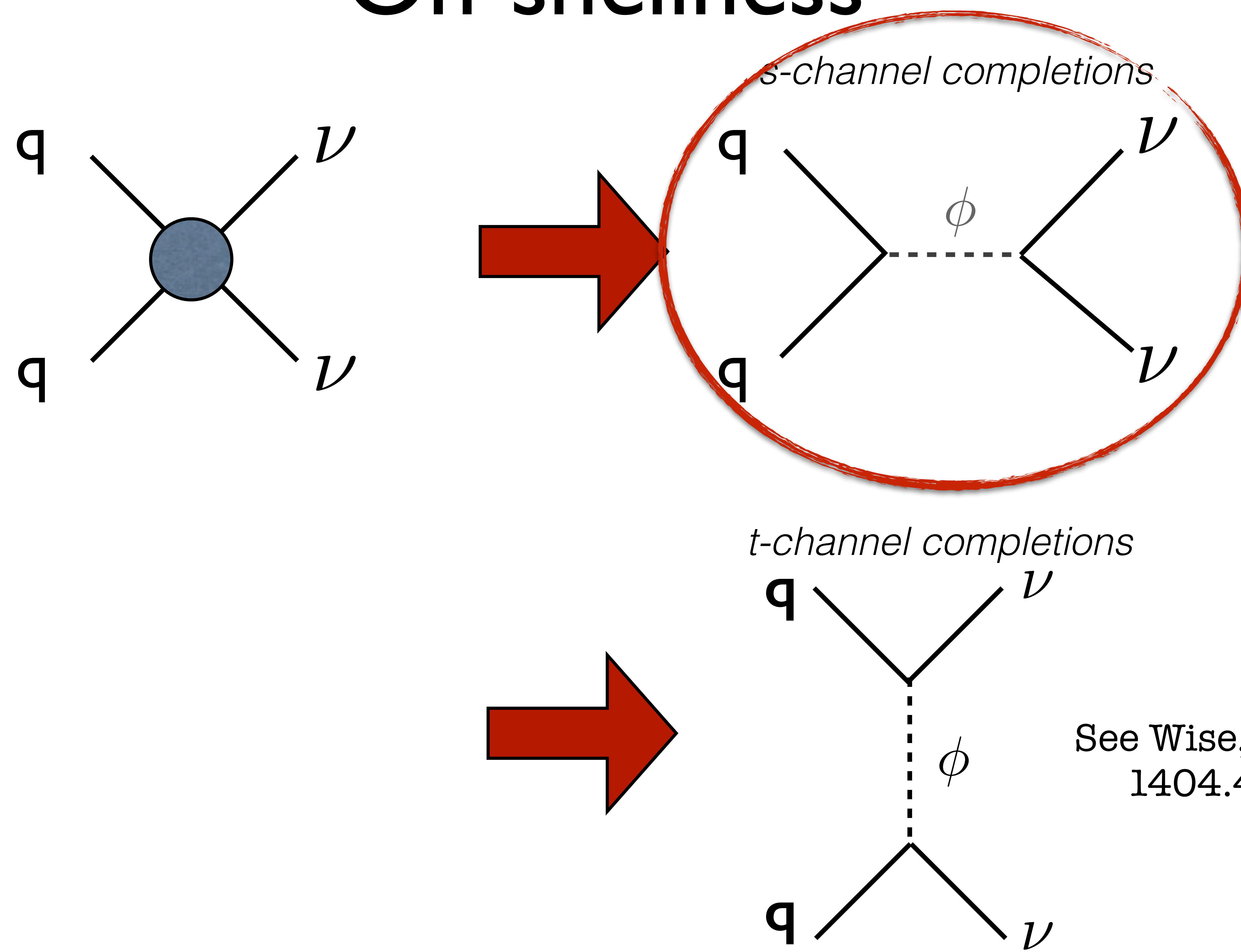
On-shellness



EFT is much simpler, BUT only valid as long as the new physics scale is large compared to LHC energies.

What if it's not?

On-shellness



See Wise, Zhang
1404.4663

Phenomenological Approach

- For simplicity, we focus on a "simplified models"

$$\mathscr{L}_{\rm NSI} = g_\nu \left(\overline{\nu} P_L \gamma_\mu \nu\right) V^\mu + \left(\overline{q}\gamma_\mu (g_q^V + g_q^A \gamma^5) q\right) V^\mu,$$

→ Still fairly general, while avoiding some of the pitfalls of Eff. Ops at LHC energies (see. e.g. Vecchi, IMS (2011), Buchmueller et al (2013)).

- Core goal is how to discriminate this NSI Lagrangian from its DM cousin:

$$\mathscr{L}_{\rm DM} = g_X \left(\overline{X} P_L \gamma_\mu X\right) V^\mu + \left(\overline{q}\gamma_\mu (g_q^V + g_q^A \gamma^5) q\right) V^\mu + m_X \overline{X} X$$

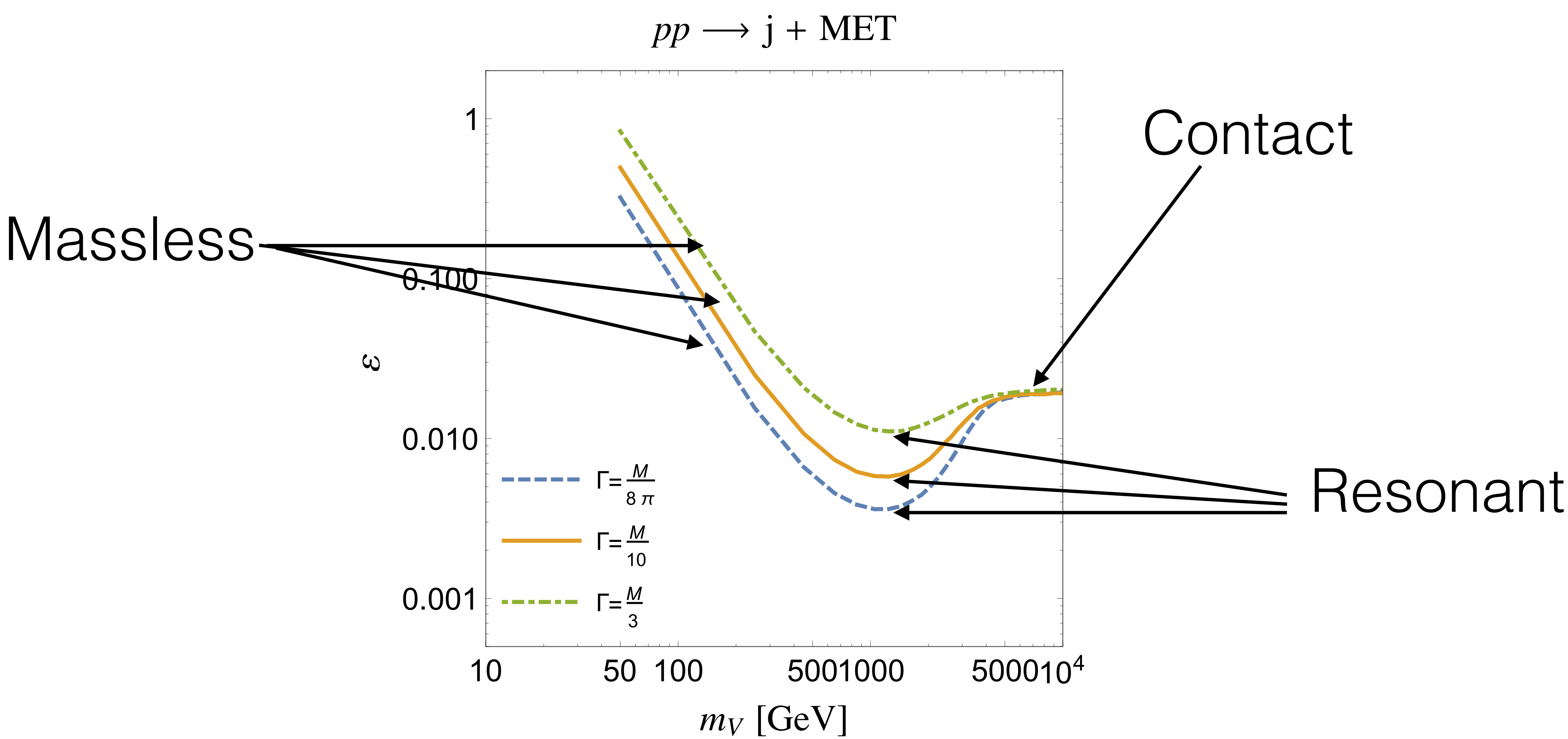
8 TeV CMS limits

EXO-12-048-pas

E_T^{miss} (GeV) →	> 250	> 300	> 350	> 400	> 450
Z($\nu\nu$)+jets	30600 ± 1493	12119 ± 640	5286 ± 323	2569 ± 188	1394 ± 127
W+jets	17625 ± 681	6042 ± 236	2457 ± 102	1044 ± 51	516 ± 31
$t\bar{t}$	470 ± 235	175 ± 87.5	72 ± 36	32 ± 16	13 ± 6.5
Z($\ell\ell$)+jets	127 ± 63.5	43 ± 21.5	18 ± 9.0	8 ± 4.0	4 ± 2.0
Single t	156 ± 78.0	52 ± 26.0	20 ± 10.0	7 ± 3.5	2 ± 1.0
QCD Multijets	177 ±88.5	76 ±38.0	23 ±11.5	3 ±1.5	2 ±1.0
Total SM	49154 ± 1663	18506 ± 690	7875 ± 341	3663 ± 196	1931 ± 131
Data	50419	19108	8056	3677	1772
Exp. upper limit	3580	1500	773	424	229
Obs. upper limit	4695	2035	882	434	157

Downward fluctuation in bkg, giving stronger than expected limits.

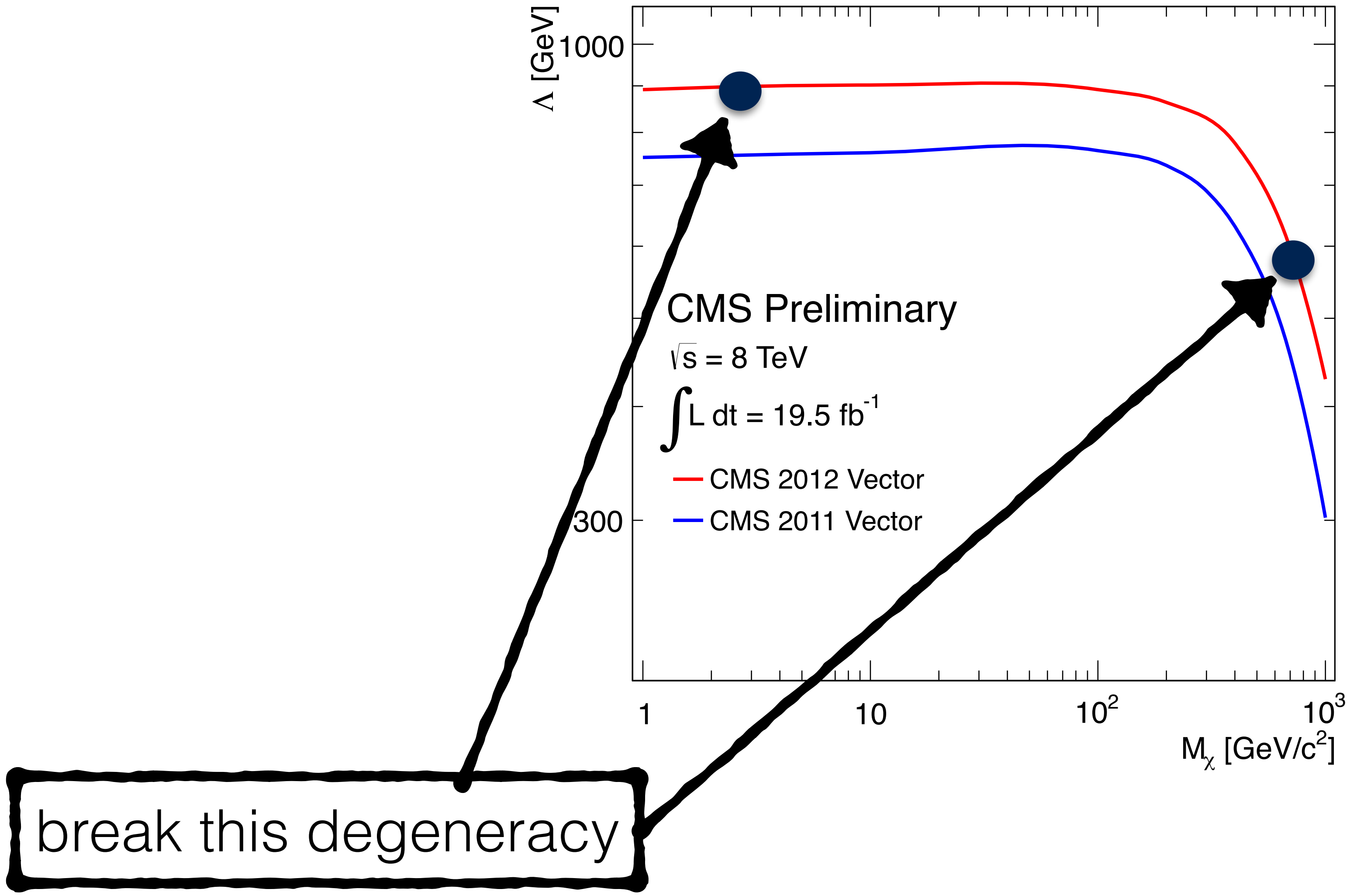
Zeroth Order Step: cut and count limit



See also Friedland, Graesser, IMS, Vecchi (2011).

Can monojets alone say something useful about DM-NSI degeneracy?

- In the event of a future discovery, use the jet pT distribution to tease out mass information.



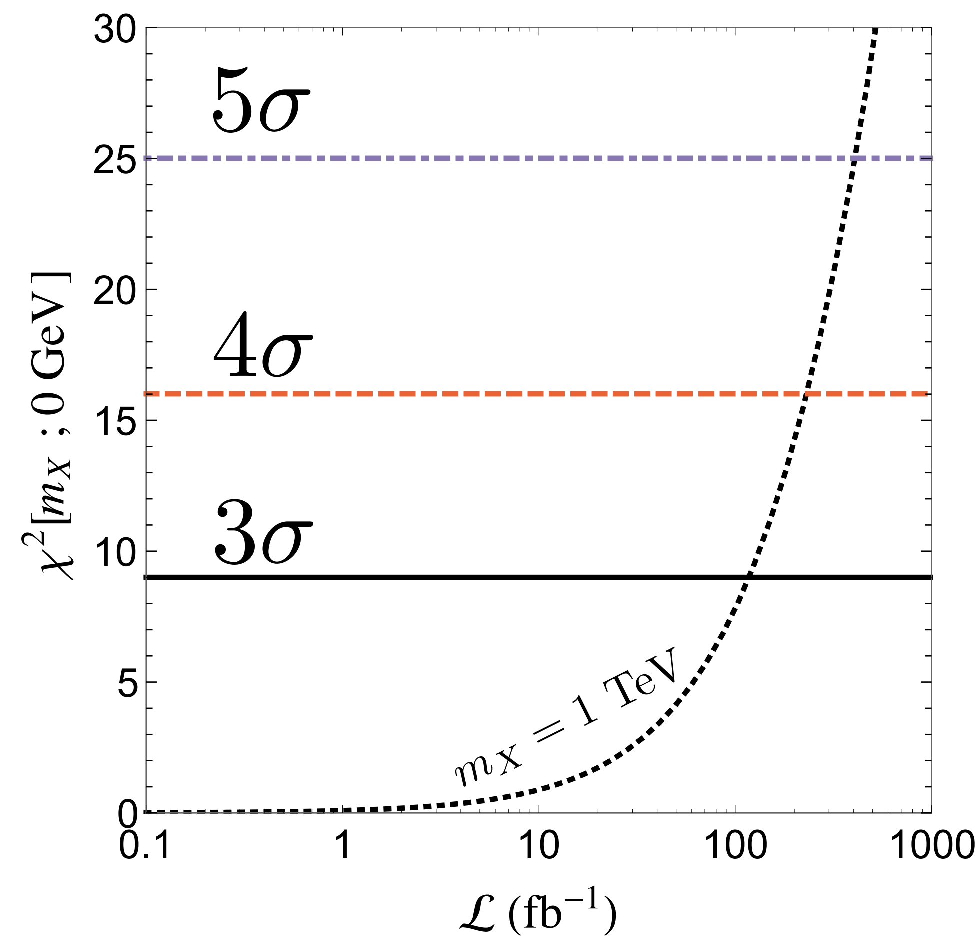
Monojet sensitivity to "invisible mass"

- Most obvious difference between neutrino and DM missing energy: final state mass!
  - Can appear in pT shape.

$$\chi^2[m_X; 0\ \mathrm{GeV}] = \sum_i \left[\frac{S_i(m_X) - S_i(0\,\mathrm{GeV})}{\sigma_i}\right]^2$$

$$\mathrm{stat.} \oplus 10\ \%\ \mathrm{sys.}$$

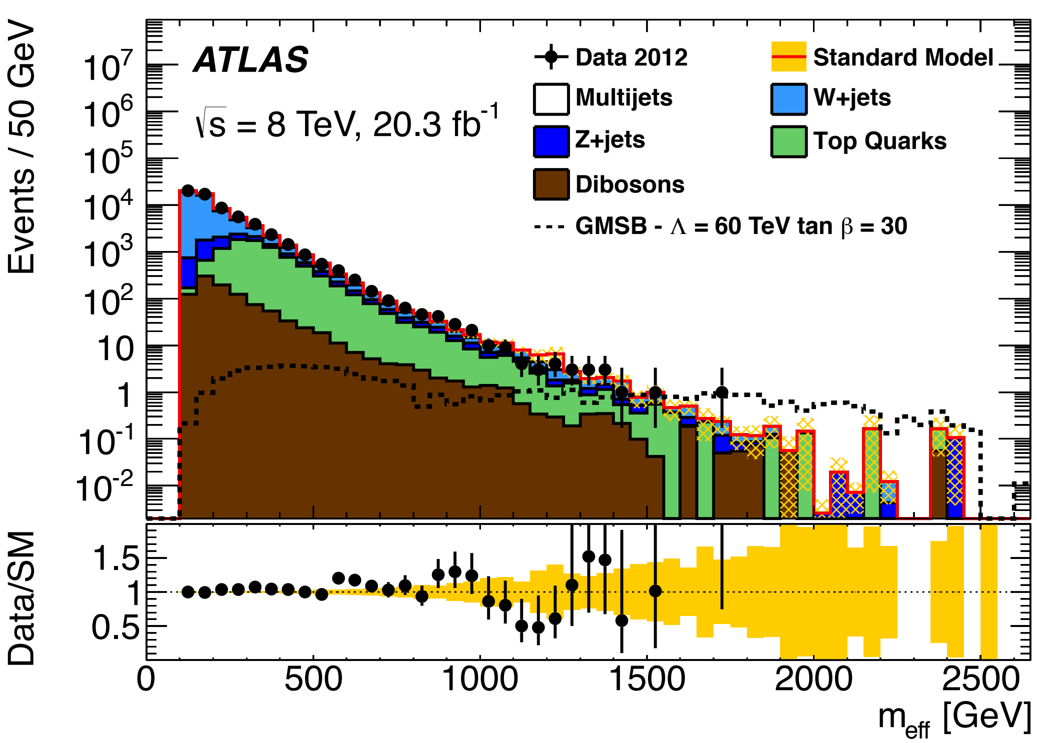
$\sqrt{s} = 13$ TeV

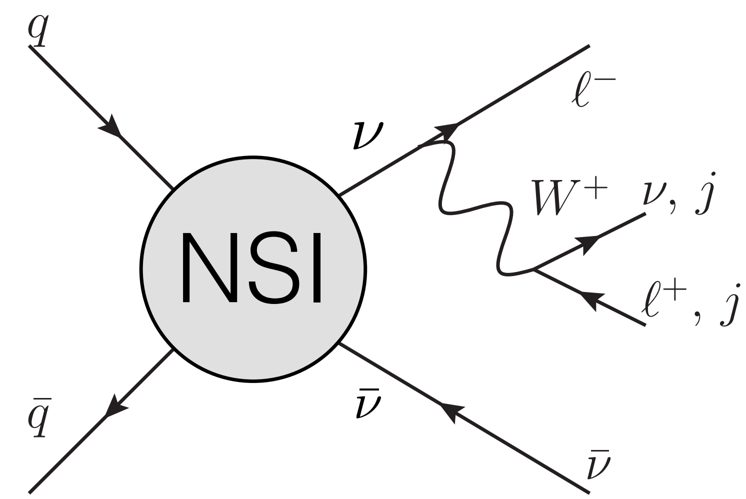


→ NSI and heavy DM are indeed distinguishable with pT shape.

Multi-lepton constraints on NSI

[1407.0603]





- Again re-purpose existing searches.

(1) e/mu NSI: [1503.04677]

$$pp \to \bar{\nu} + W^{\pm}\ell^{\mp},\ W^{\pm} \to jj,\ \ell = e,\ \mu$$

(2) tau NSI: [1407.0603]

$$pp \to \bar{\nu} + W^{\pm}\tau^{\mp},\ W^{\pm} \to \ell\nu,\ \tau \to \textbf{hadrons},\ \ell = e,\ \mu$$

$$m_{\text{eff}} = H_{\mathrm{T}}^{2\mathrm{j}} + E_{\mathrm{T}}^{\text{miss}}$$

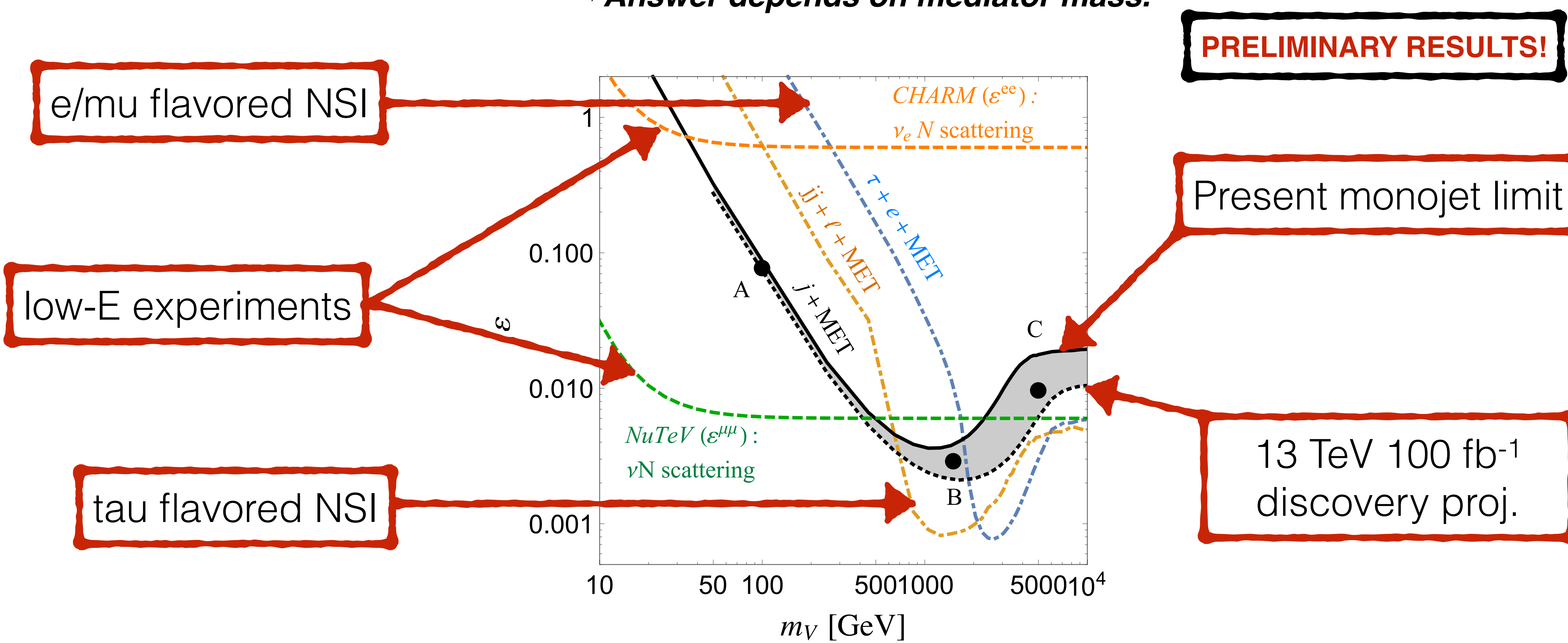
$$H_{\mathrm{T}}^{2\mathrm{j}} = \sum_{\text{all }\ell} p_{\mathrm{T}}^{\ell} + \sum_{\text{all }\tau} p_{\mathrm{T}}^{\tau} + \sum_{i=1,2} p_{\mathrm{T}}^{\text{jet}_i}$$

See also: Davidson, Sanz [1108.5320],
Graesser, Friedland, IMS, Vecchi, [1111.5331].

Experimental Complementarity

- Even if low-m_V NSI escapes LHC constraints, there are a variety of low-energy probes.
  - ➡ ν-N scattering measurements from e.g. CHARM, NuTeV, etc.
  - ➡ General trend: heavy mediators are most strongly constrained by LHC data.

- How does this aid in neutrino-DM discrimination?
  - ➡ ***Answer depends on mediator mass.***



Experimental Complementarity

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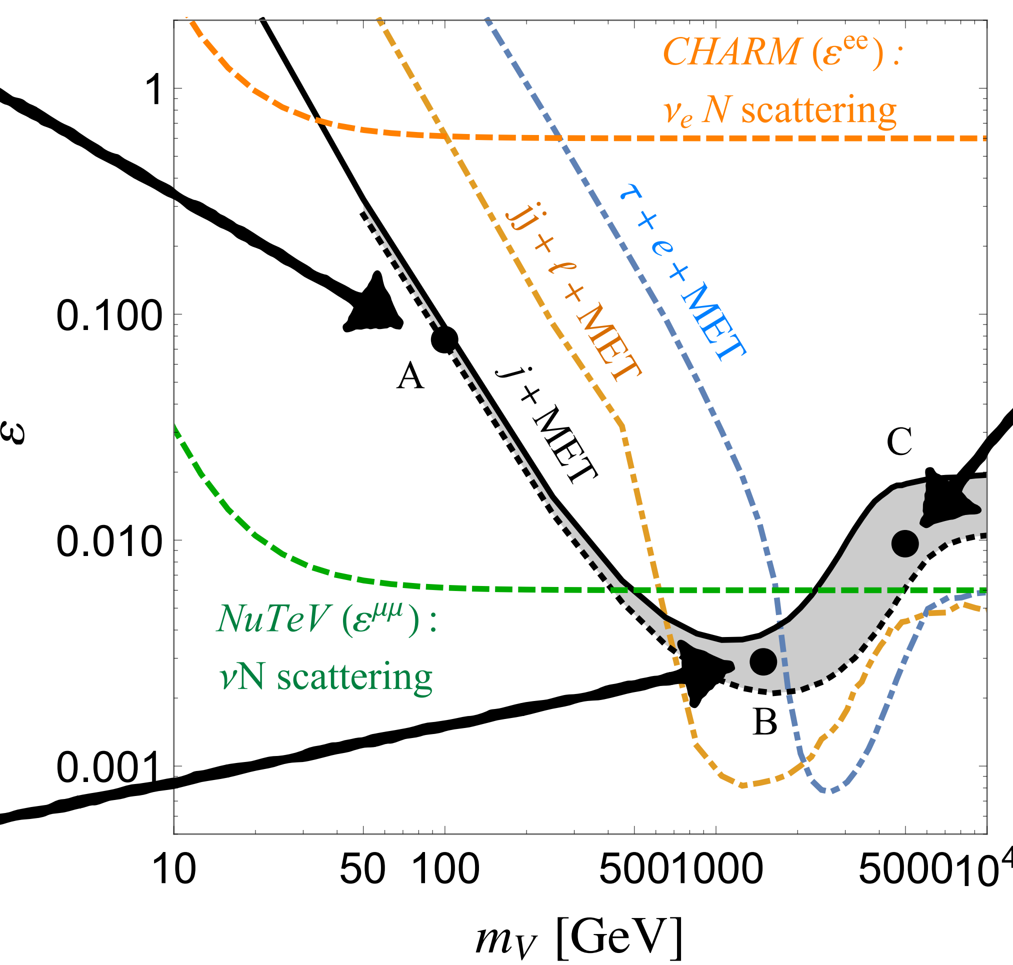
Benchmark A:
- LHC not useful tool for discrimination.
- Orthogonal data (νN scattering or direct detection) needed.

Benchmark B (e/mu NSI):
- Monojet "BSM discovery" potential.
- jj+l+MET helps discriminate NSI from DM.

How does this aid in neutrino-DM discrimination?

➡ ***Answer depends on mediator mass.***



Benchmark C (e/mu/tau NSI):
- LHC data is sufficient to exclude NSI as an explanation.

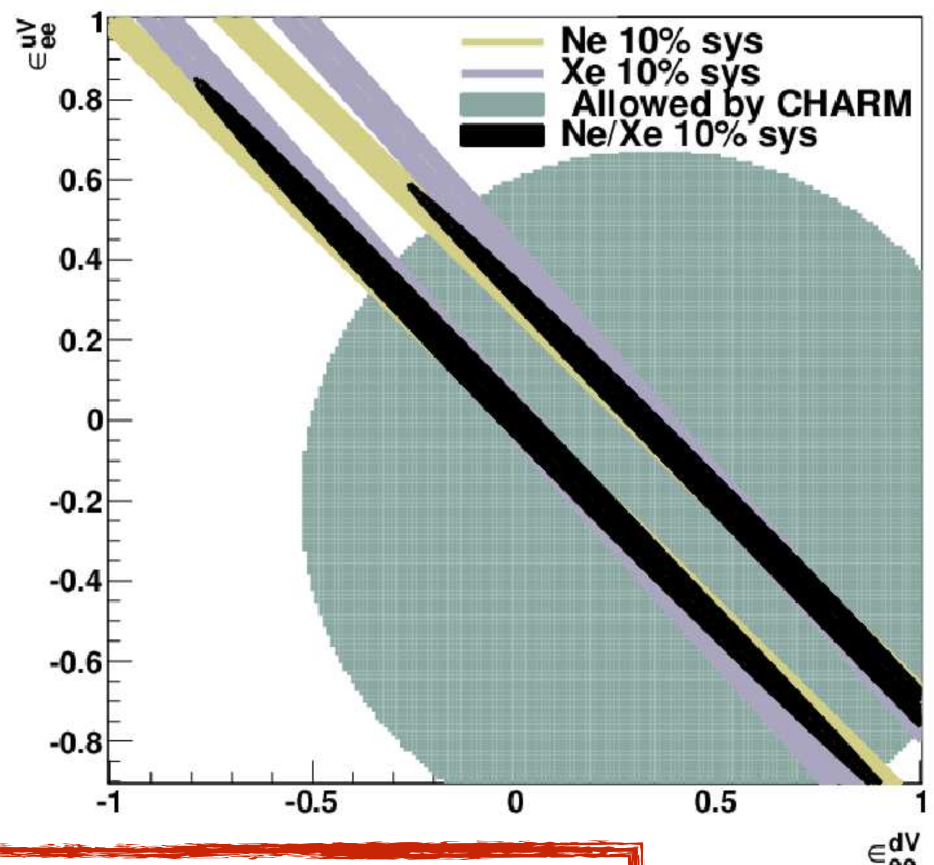
FUTURE CONSTRAINTS

COHERENT improvements

- Coherent elastic neutral current scattering has yet to be detected.
- A neutrino of any flavor scatters off a nucleus at low momentum transfer Q such that the nucleon wavefunction amplitudes are in phase and add coherently.

K. Scholberg (2005)

$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2ME)\left[1-\frac{ME}{2k^2}\right]\times$$
$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$
$$+\sum_{\alpha\neq\beta}[Z(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}) + N(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV})]^2\},$$



COHERENT collaboration looking at CsI, Ge and LXe targets to get reasonable exposures in 5 years.

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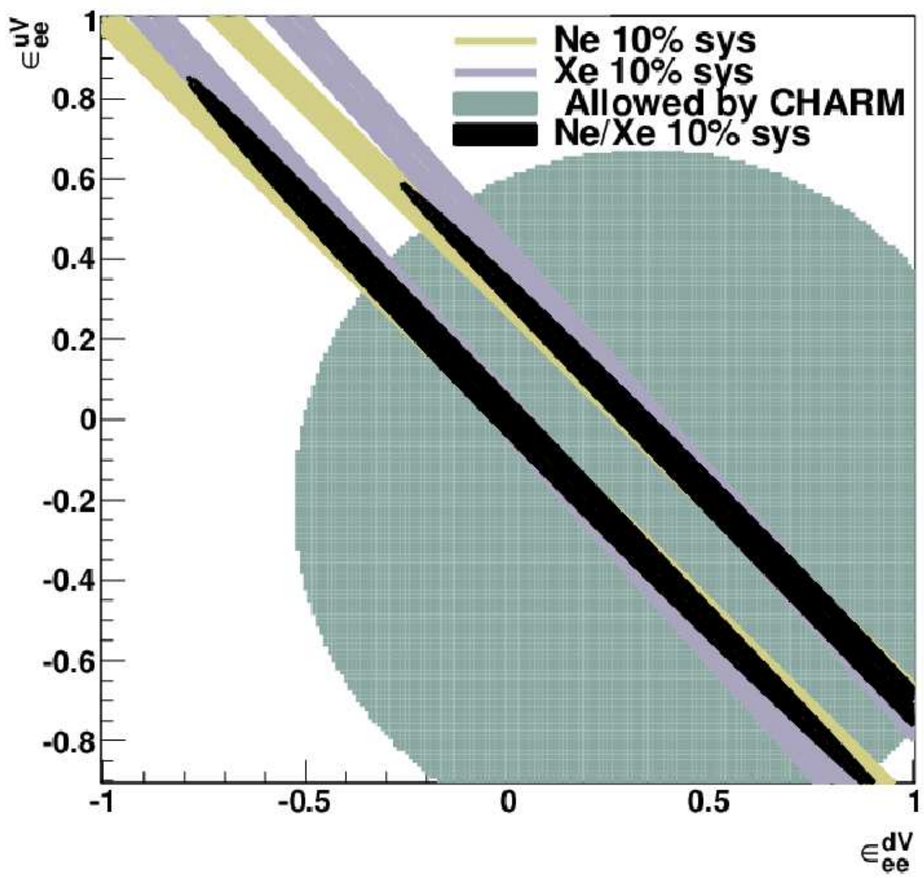
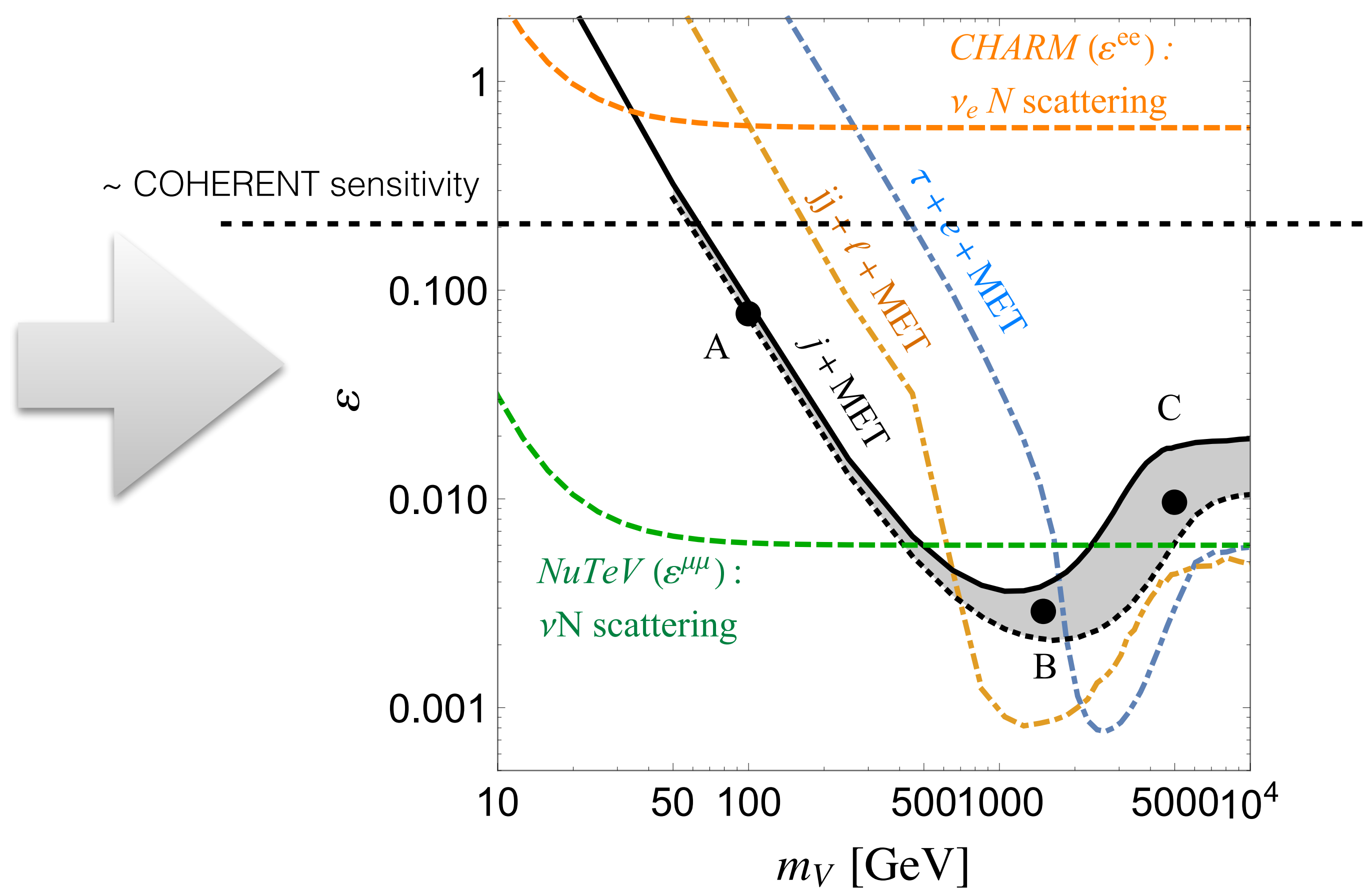
K. Scholberg (2005)





Coming soon

- More probes are on the way:

  - **Long-baseline probes**: NOvA, DUNE (see A. Friedland, IMS [1207.6642])

  - **Solar**: ton-scale DM experiments (see Billard, Strigari, Figueroa-Feliciano [1409.0050])

  - **Neutrino-nucleus scattering**: COHERENT.

  - **Atmospheric data**: IceCube DeepCore (see Warren Wright's talk this afternoon).

Conclusions

PART I

- Alternative thermal relics can be probed at direct detection.
- Masses as low as 10 MeV are detectable, and with distinct recoil spectra.
- Simple method to compare **relativistic** interpretations of direct detection data.

PART II

- ***Heavy DM*** can be discriminated from NSI with monojet data alone with pT shape information.
- ***Light DM*** is more difficult, but can be discriminated from ***heavy mediator-NSI*** using multi-lepton channels.
    - ***Light mediator-NSI*** is difficult to constrain at the LHC: best at faking (light) DM.
    - Highlights the need for additional low-energy probes.