Dark Matter Theory Overview

Patrick Fox

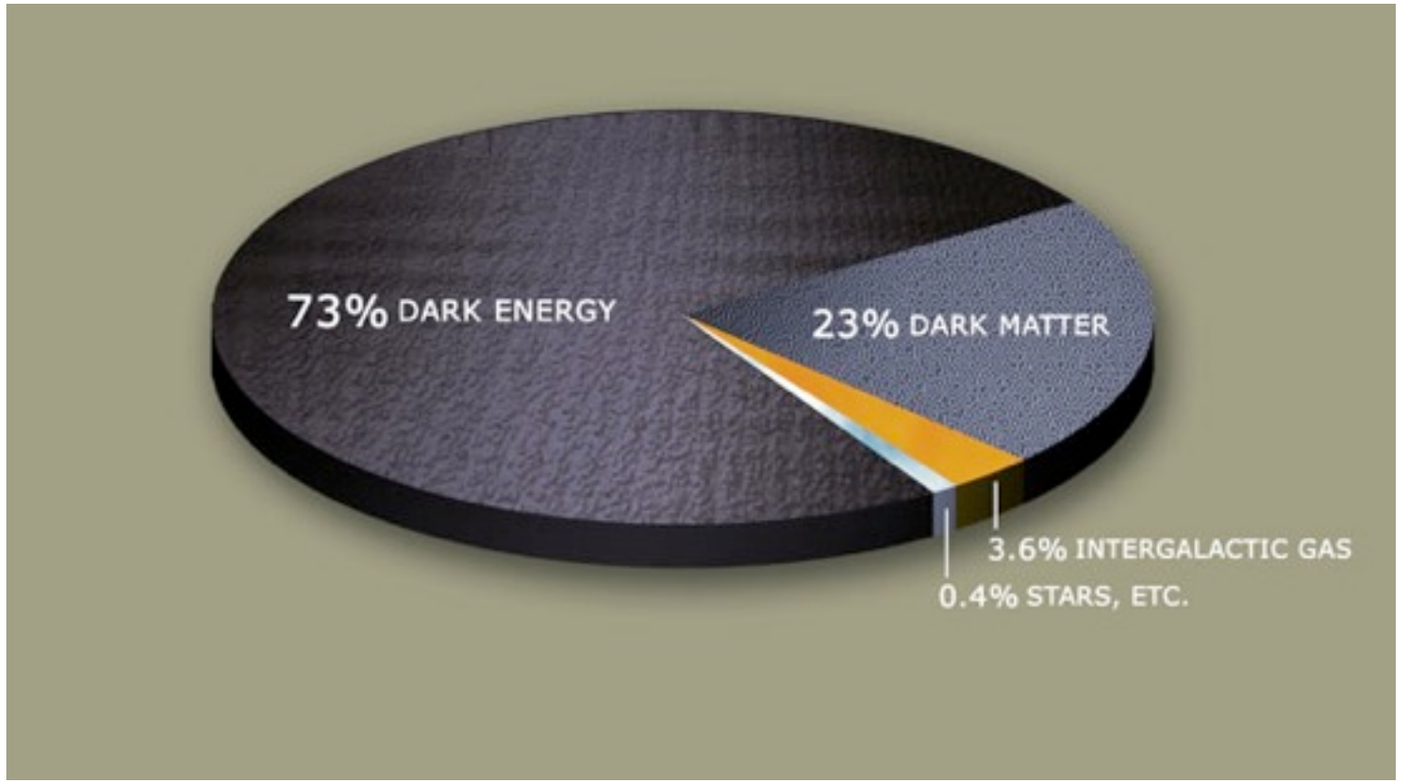
Fermilab

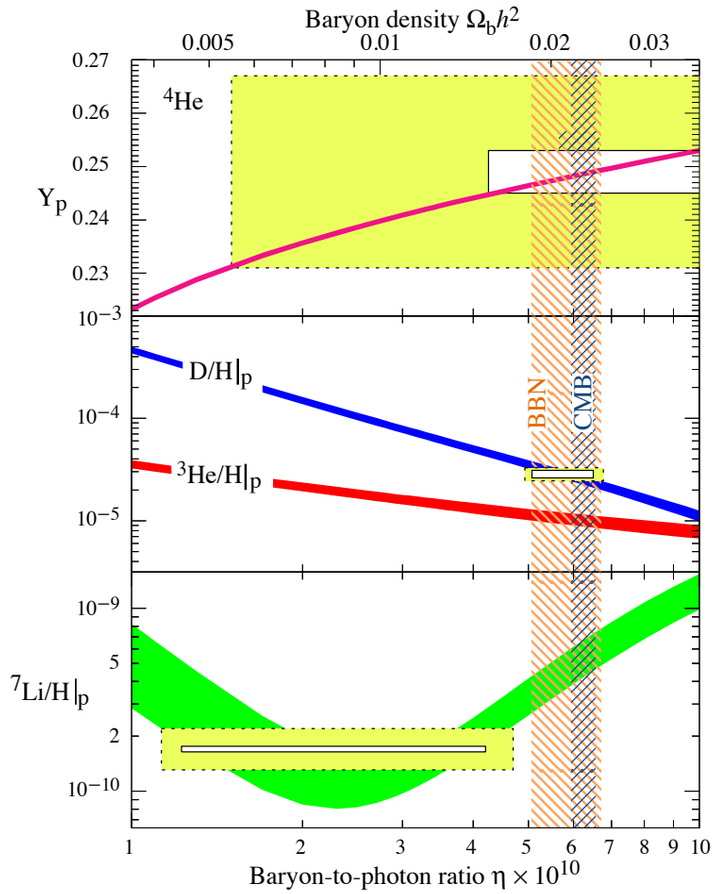
DM at a future Hadron Collider, FNAL 2015

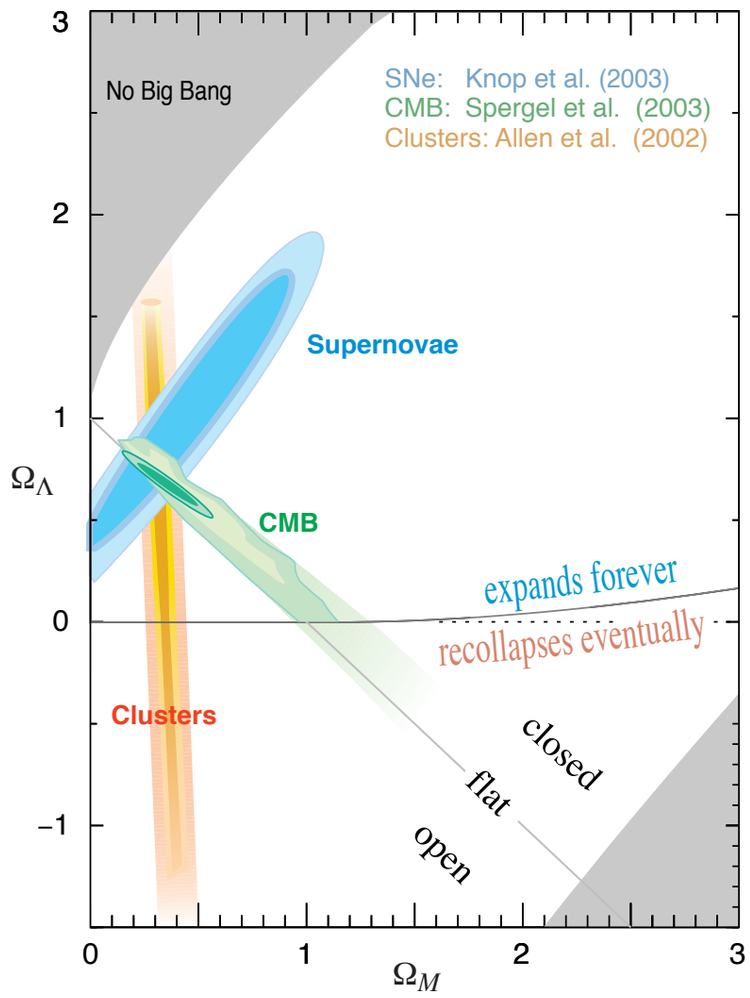
Outline

- Evidence for DM, and its gross properties
- Some candidates
- Relic abundance and thermal DM
- WIMP DM
  - Direct detection
  - Indirect detection
  - Astrophysical probes
  - Collider searches
- Conclusions

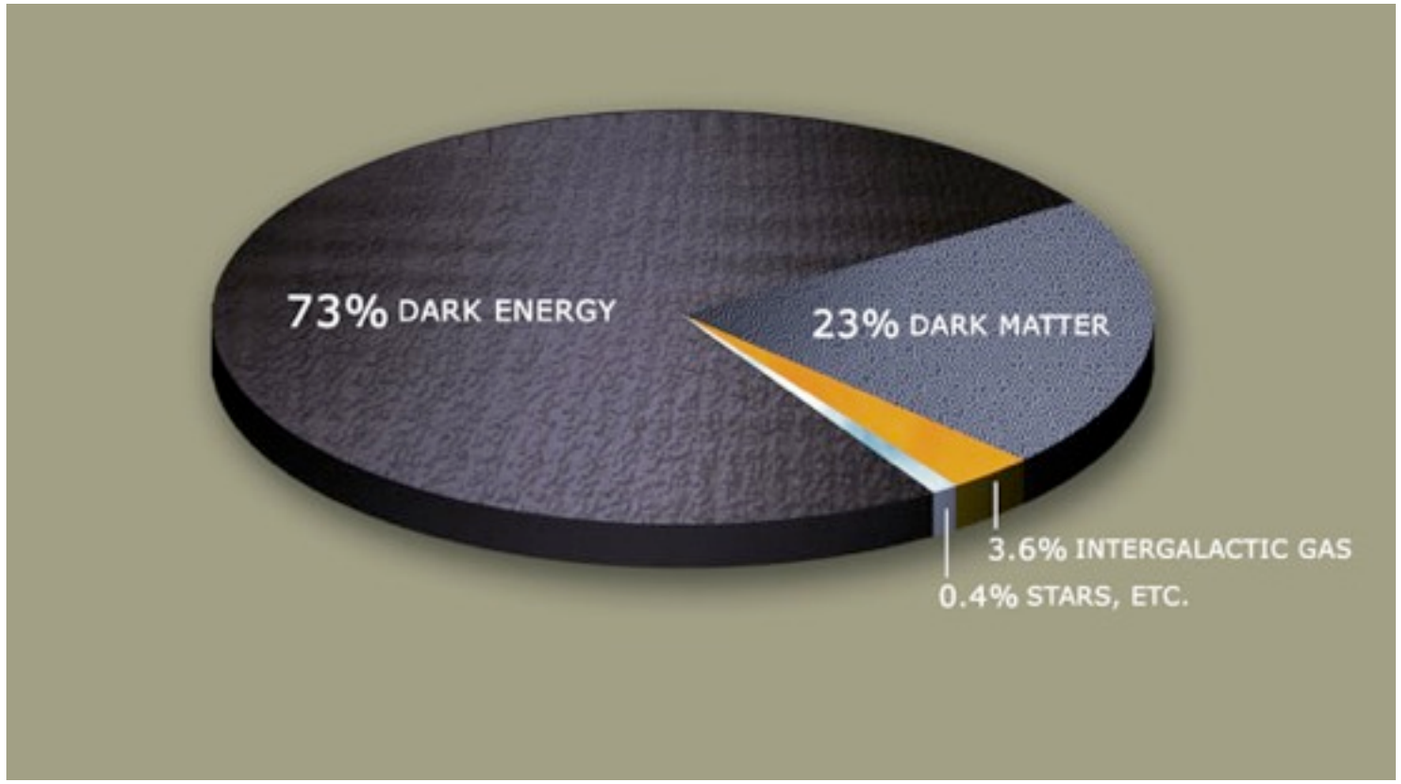
Everything


73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

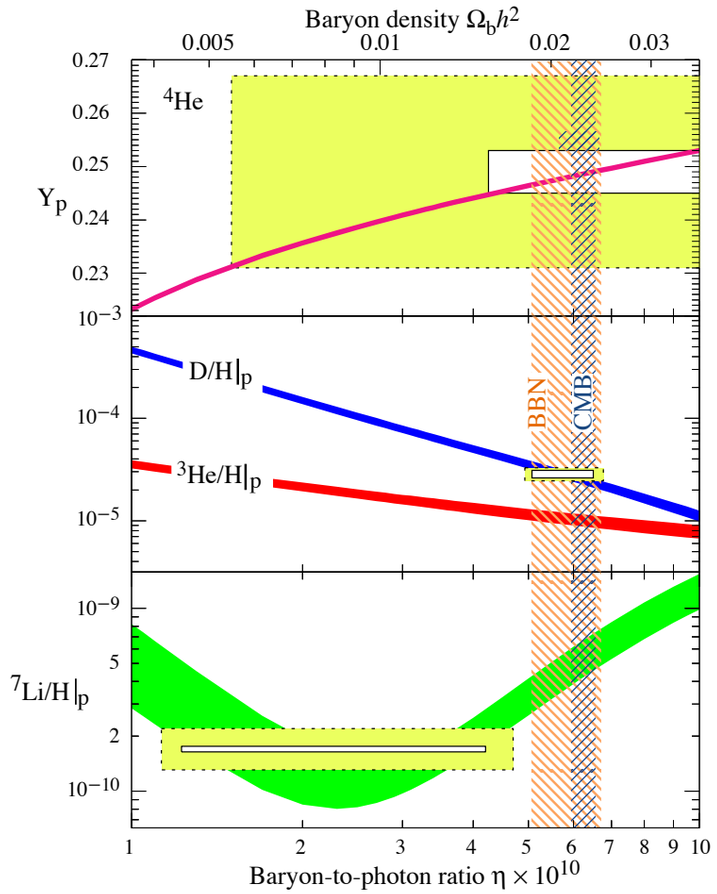

Baryon density $\Omega_b h^2$
0.005
0.01
0.02
0.03
^{4}He
Y_p
0.27
0.26
0.25
0.24
0.23
10^{-3}
D/H|$_p$
10^{-4}
^{3}He/H|$_p$
10^{-5}
BBN
CMB
10^{-9}
5
^{7}Li/H|$_p$
2
10^{-10}
1 2 3 4 5 6 7 8 9 10
Baryon-to-photon ratio $\eta \times 10^{10}$

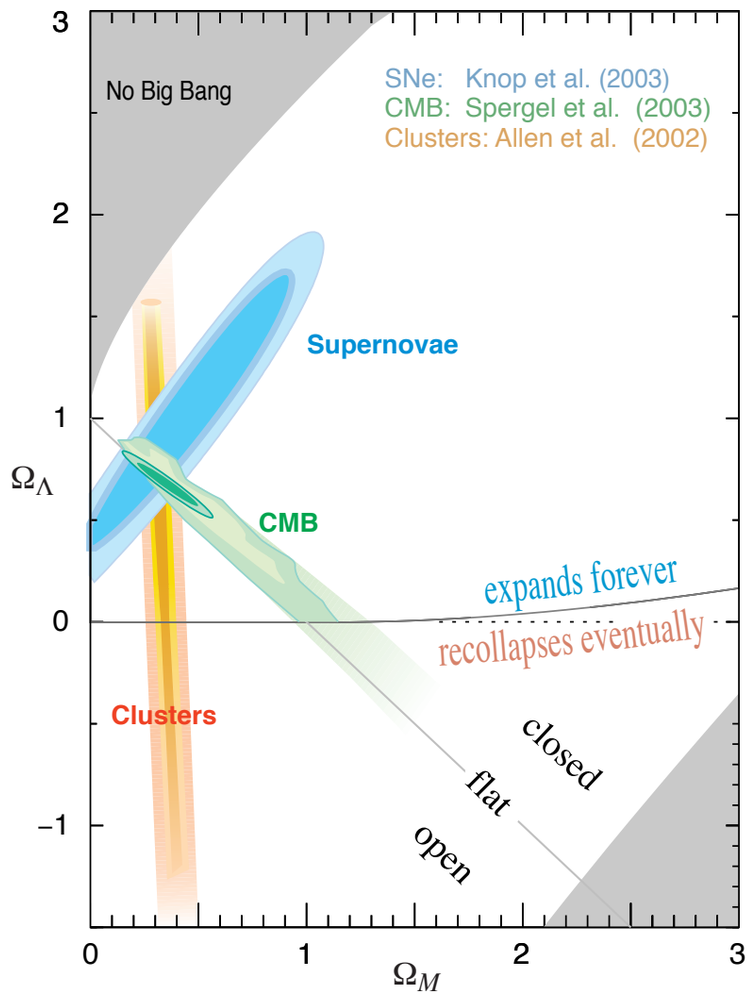

3
No Big Bang
SNe: Knop et al. (2003)
CMB: Spergel et al. (2003)
Clusters: Allen et al. (2002)
2
Supernovae
1
Ω_Λ
CMB
expands forever
recollapses eventually
0
Clusters
closed
flat
open
−1
0 1 2 3
Ω_M

Everything



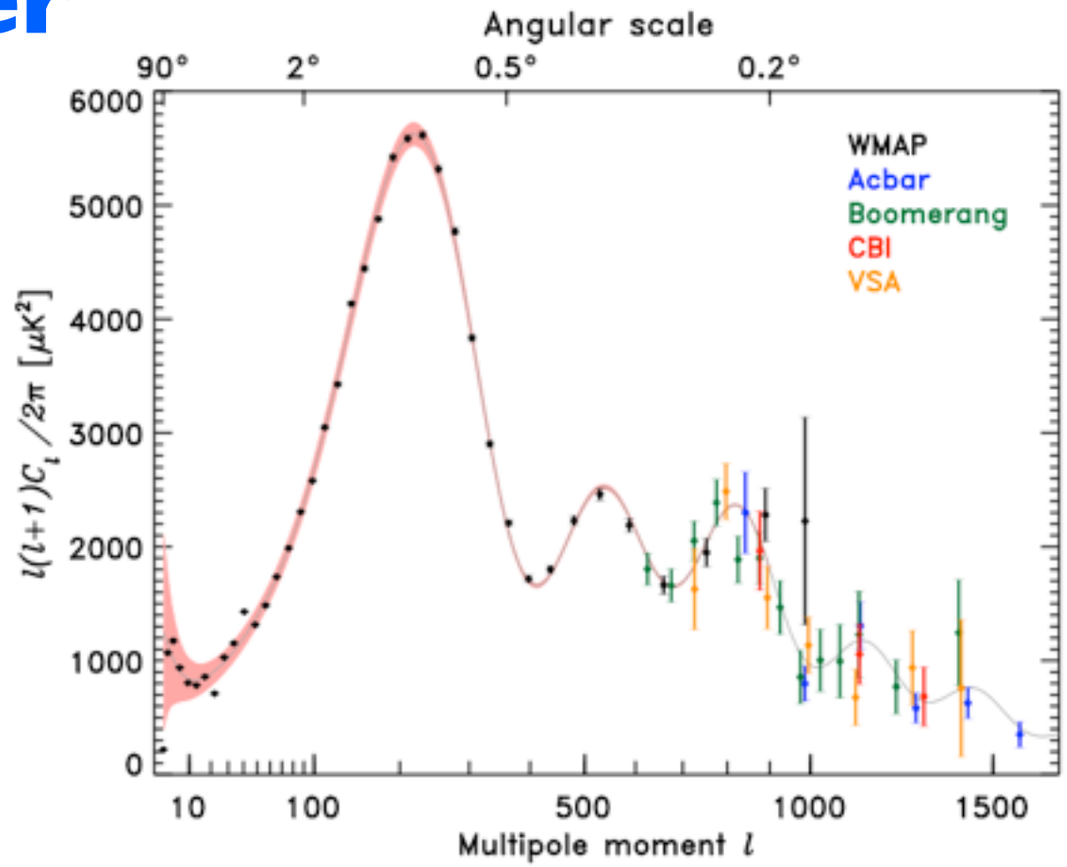
- 23% of universe energy/matter is a new type of (non-baryonic) matter
- 73% is a new type of energy (cosmological constant)
- SM is 4%



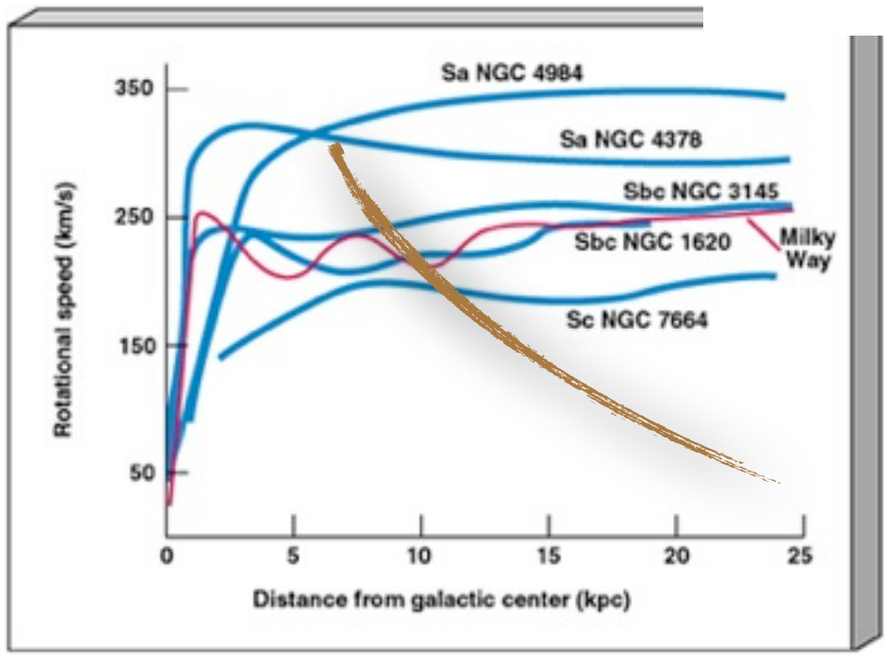


Evidence for Dark Matter

Coma Cluster



CMB, LSS etc



Galactic rotation curves

e.g. Bullet cluster

Recap on DM's (gross) properties

- DM makes up 23% of the universe
- Gravitates like ordinary matter, but is non-baryonic
- Is dark i.e. neutral under SM (not coloured, or charged)
- Does not interact much with itself $\frac{\sigma_{\chi\chi}}{m_\chi} \lesssim 100\,\mathrm{GeV}^{-3}$
- Does not couple to massless particle
- Was no relativistic at time of CMB
- Is long lived (>10^22 s!)

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No such particle exists in the SM

Axions

Primordial Black holes

?

MACHOs

Sterile neutrinos

?

WIMPs

Q-balls

Axions

?

Primordial Black holes

Sterile neutrinos

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Q-balls

WIMPs

DM as a thermal relic

"The weak shall inherit the Universe"

If there are DM-SM couplings leading to annihilation/ production, DM will be produced in the hot early universe

$$T \gg m_\chi : \; n_\chi^{eq} \sim T^3 \qquad \chi\chi \leftrightarrow \bar{f} f$$

$$T \lesssim m_\chi : \; n_\chi^{eq} = g \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi/T} \qquad \chi\chi \rightarrow f \bar{f}$$

Universe is expanding while this is happening
Need to solve Boltzmann equation

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_{eq}^2 \right)$$

$$H = \frac{\dot{a}}{a} \sim \frac{T^2}{M_{pl}}$$

DM as a tl

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production, D ot early universe

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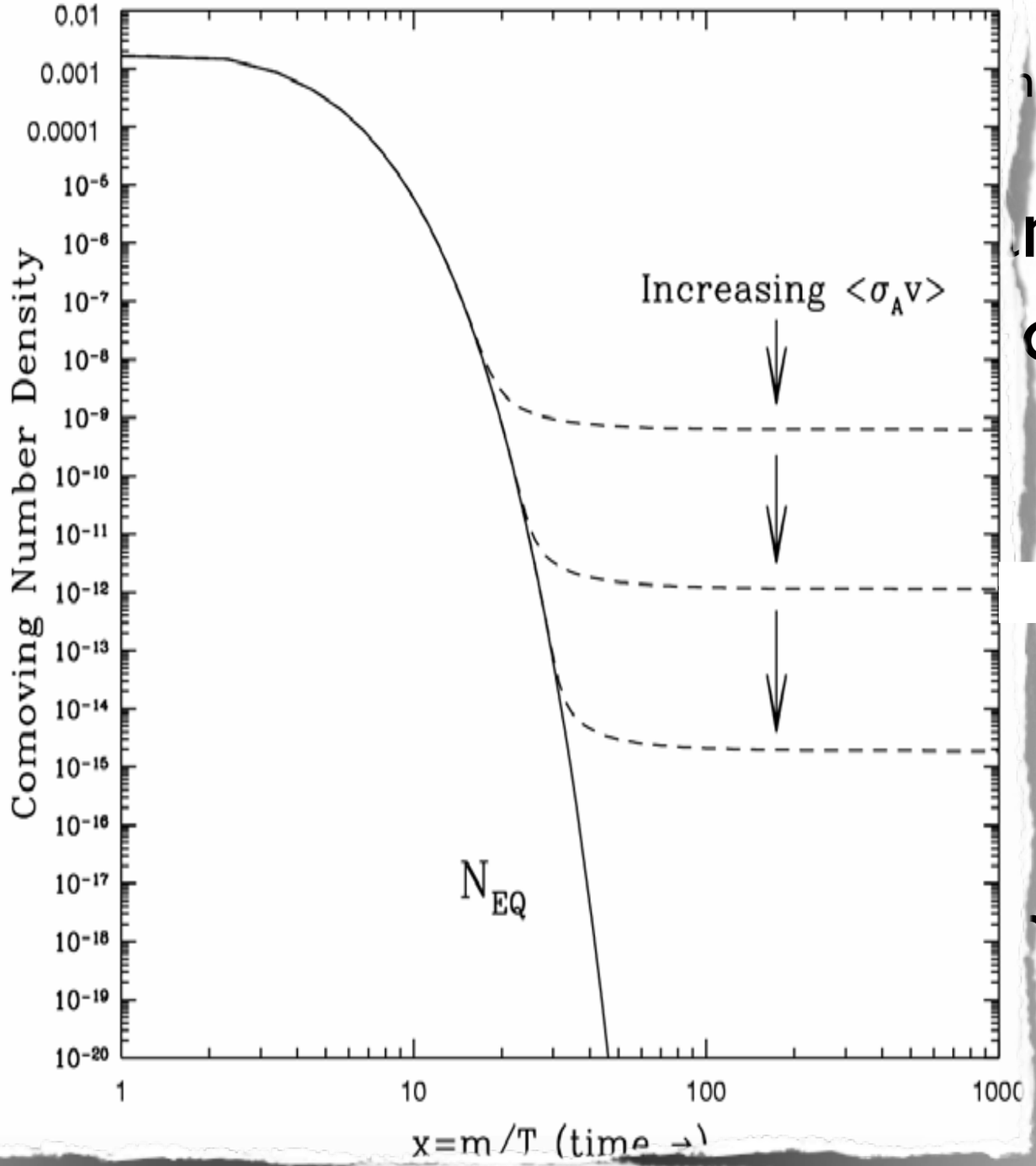

Universe s e ning
Need to solv

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Some examples

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_{eq}^2\right)$$

$\langle\sigma v\rangle = const$

Freeze out occurs when

$$\left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T} \sim \frac{T_f^2}{M_{pl}\langle\sigma v\rangle}$$

Numerical solution show x=20..30

$$\rho_c = \frac{3H^2}{8\pi G_N} = 8 \times 10^{-47} h^2 \mathrm{GeV}^{-4}$$

$$\Omega_\chi = \frac{m_\chi n_0}{\rho_c} \sim \frac{T_0^3}{\rho_c} \frac{x}{M_{pl}\langle\sigma v\rangle}$$

Some examples

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$$\rho_c = \frac{3H^2}{8\pi G_N} = 8 \times 10^{-47} h^2 \mathrm{GeV}^{-4}$$

$$\Omega h^2 \approx 0.1 \left(\frac{m/T}{20}\right) \left(\frac{g_*}{80}\right)^{-1} \left(\frac{3 \times 10^{-26} \mathrm{cm}^2 \mathrm{s}^{-1}}{\sigma v}\right)$$

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IF DM is a thermal relic:

- A weak scale annihilation x-sec gives correct abundance
- Mass range is $10\ \mathrm{MeV} \lesssim m_\chi \lesssim 70\ \mathrm{TeV}$

cold

$$\sigma v \lesssim \frac{4\pi}{m_\chi^2}$$

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WIMPs

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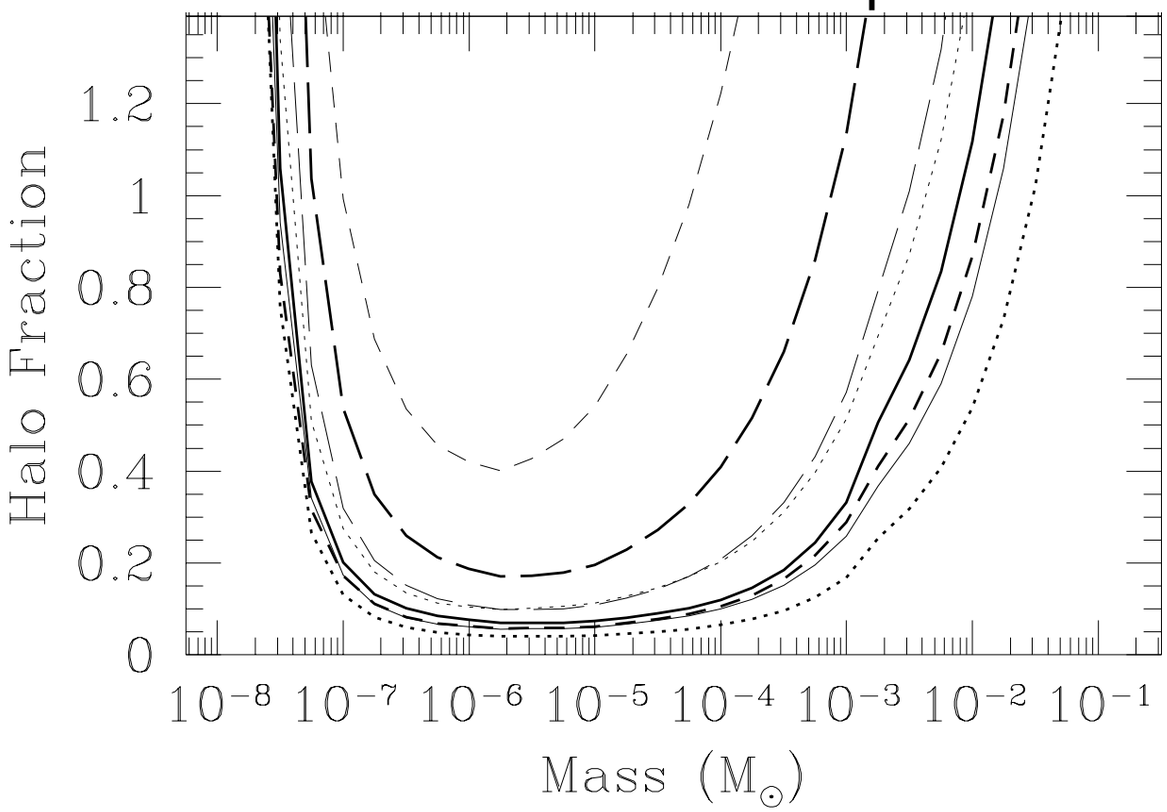
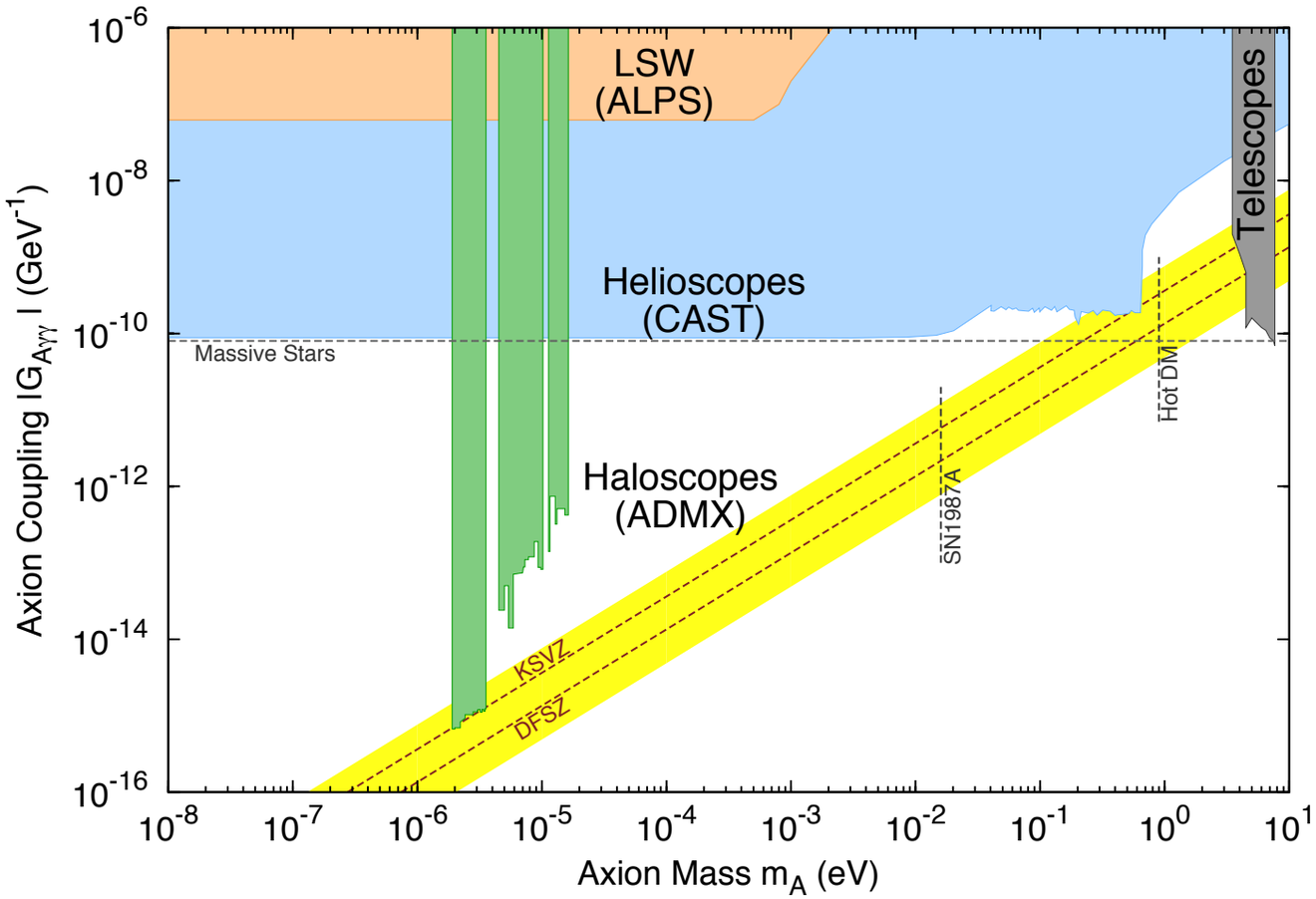
Alternatives

Macho constraints

astro-ph/9803082

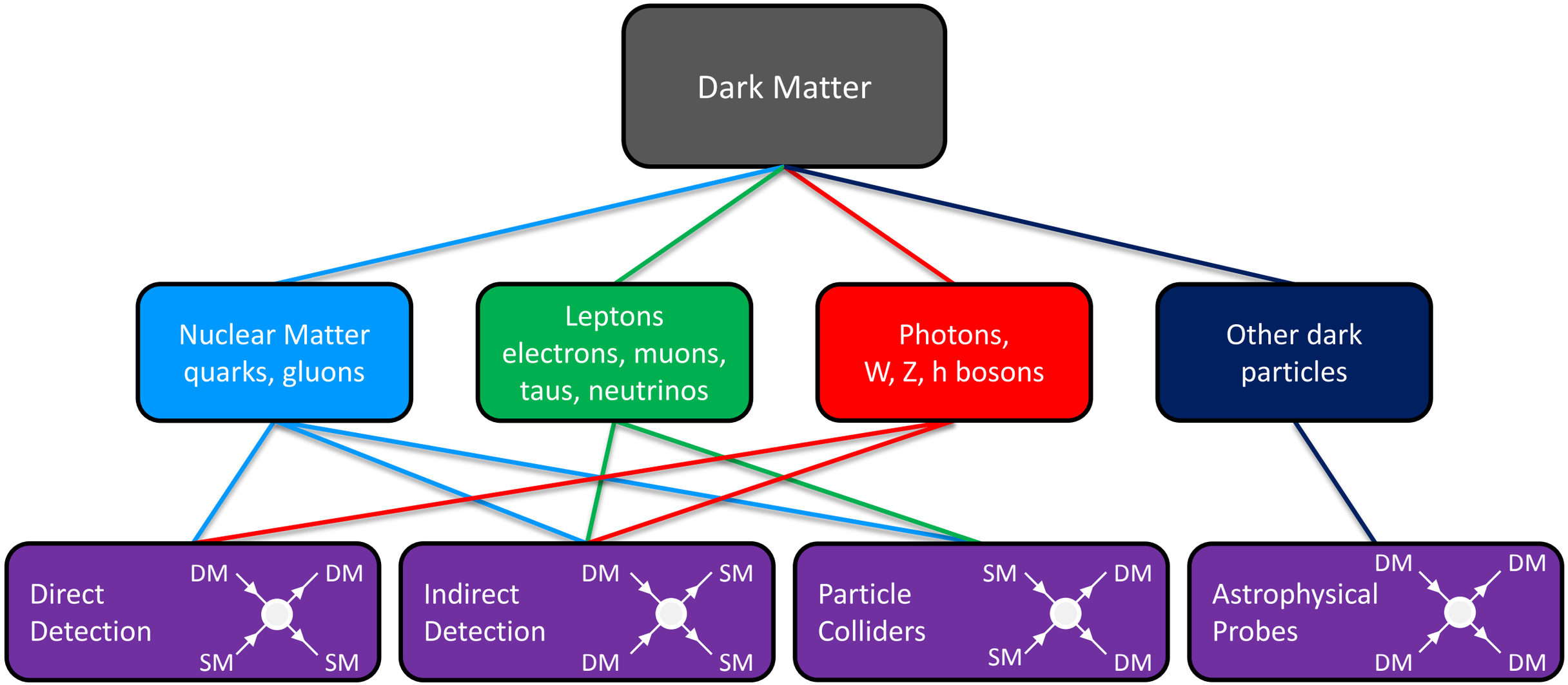


Axions

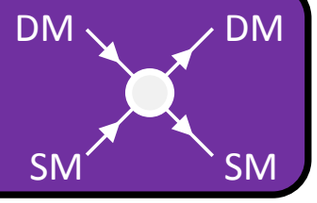


MOdified Newtonian Dynamics (Milgrom, '83)

TeVeS - puts MOND on firmer footing but seems to still have stability issues, and problems with Bullet cluster?

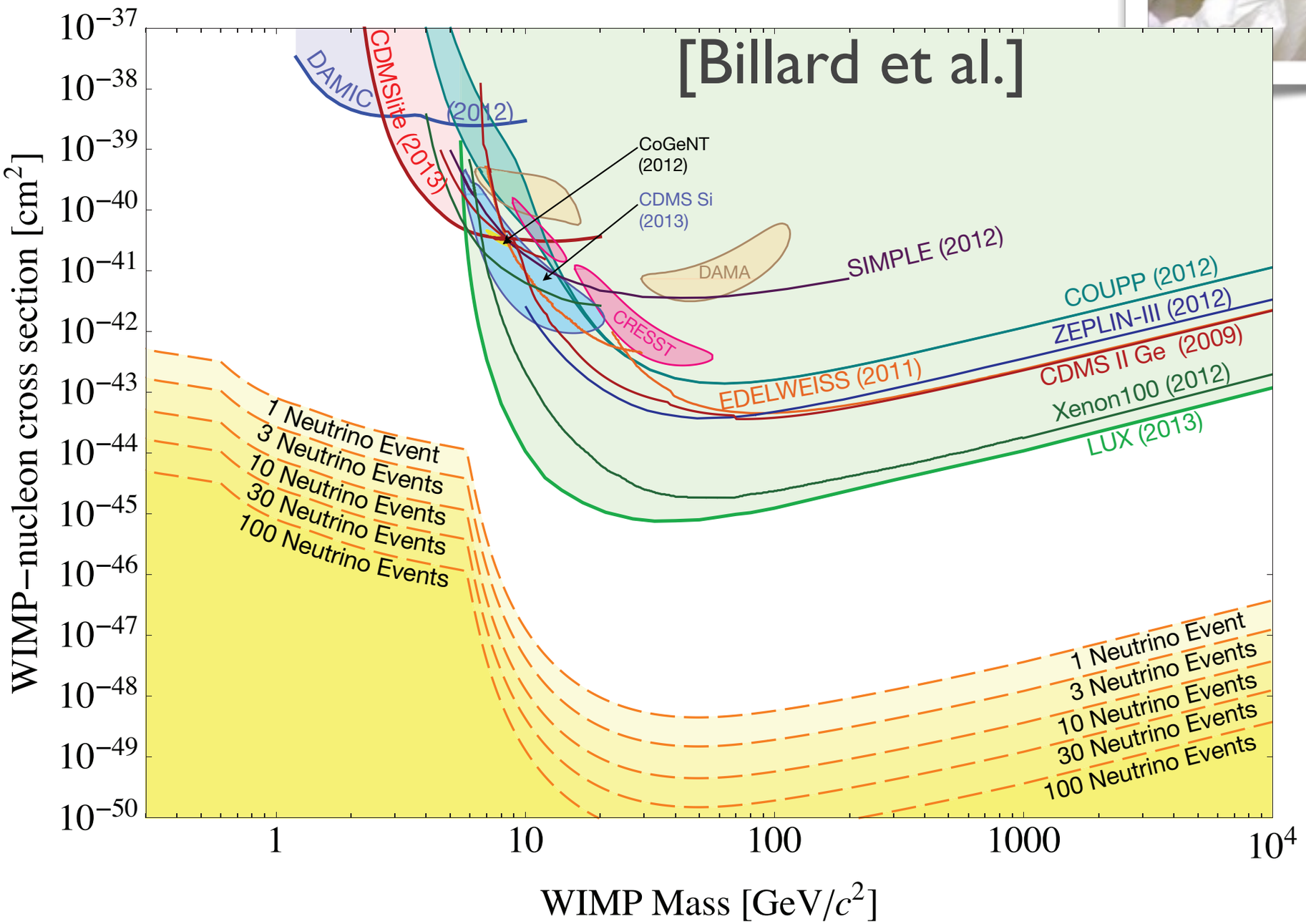

Dark Matter
Nuclear Matter
quarks, gluons
Leptons
electrons, muons,
taus, neutrinos
Photons,
W, Z, h bosons
Other dark
particles
Direct
Detection
DM
DM
SM
SM
Indirect
Detection
DM
SM
DM
SM
Particle
Colliders
SM
DM
SM
DM
Astrophysical
Probes
DM
DM
DM
DM

Direct Detection

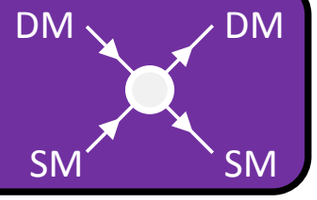


(See Andrew's talk next)

[Billard et al.]



Direct Detection



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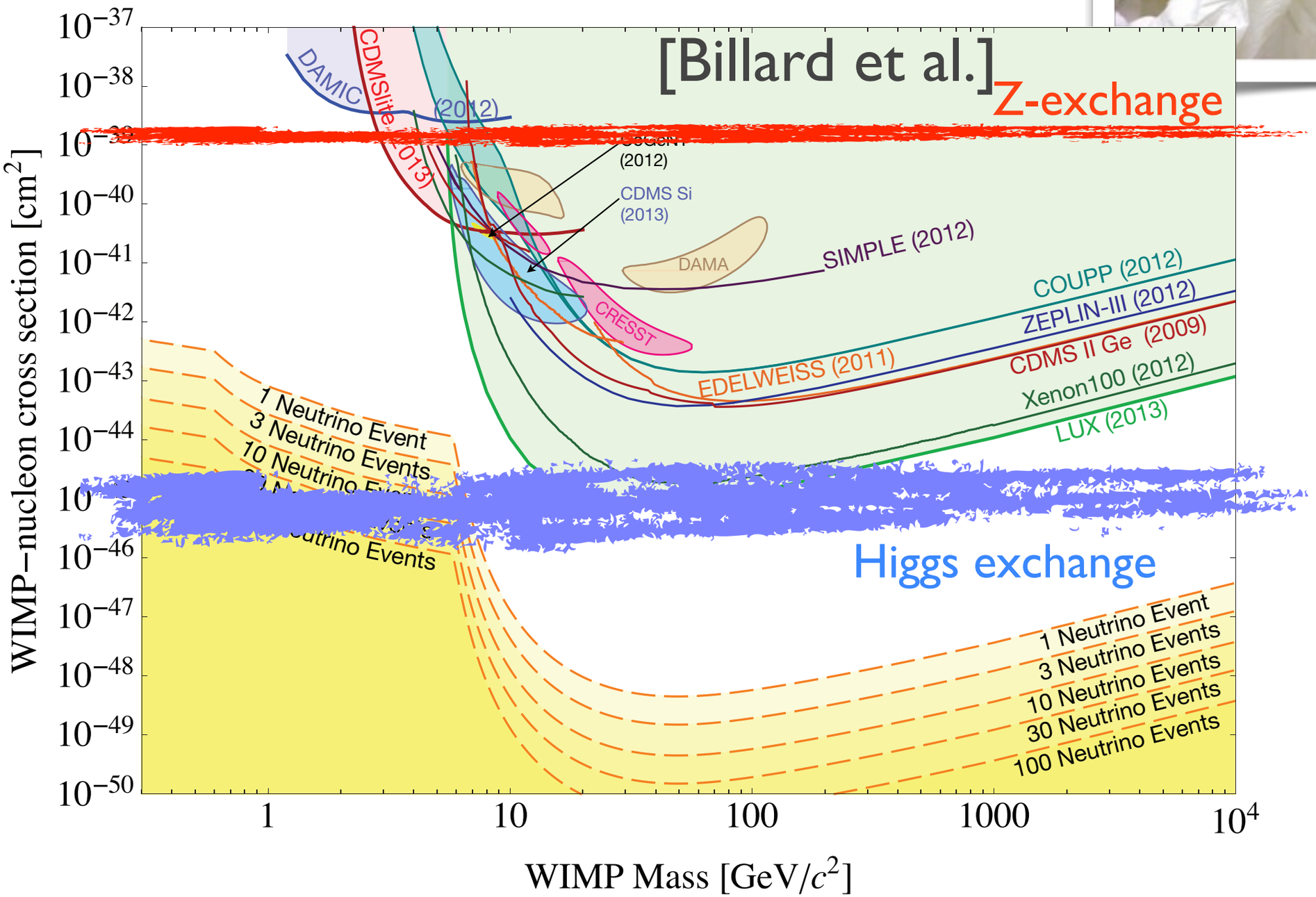
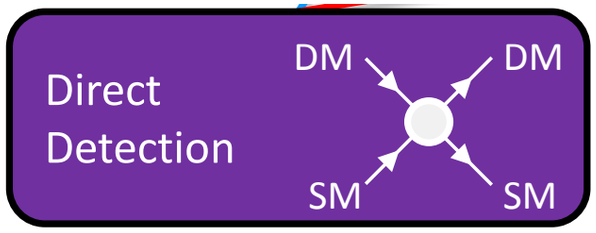
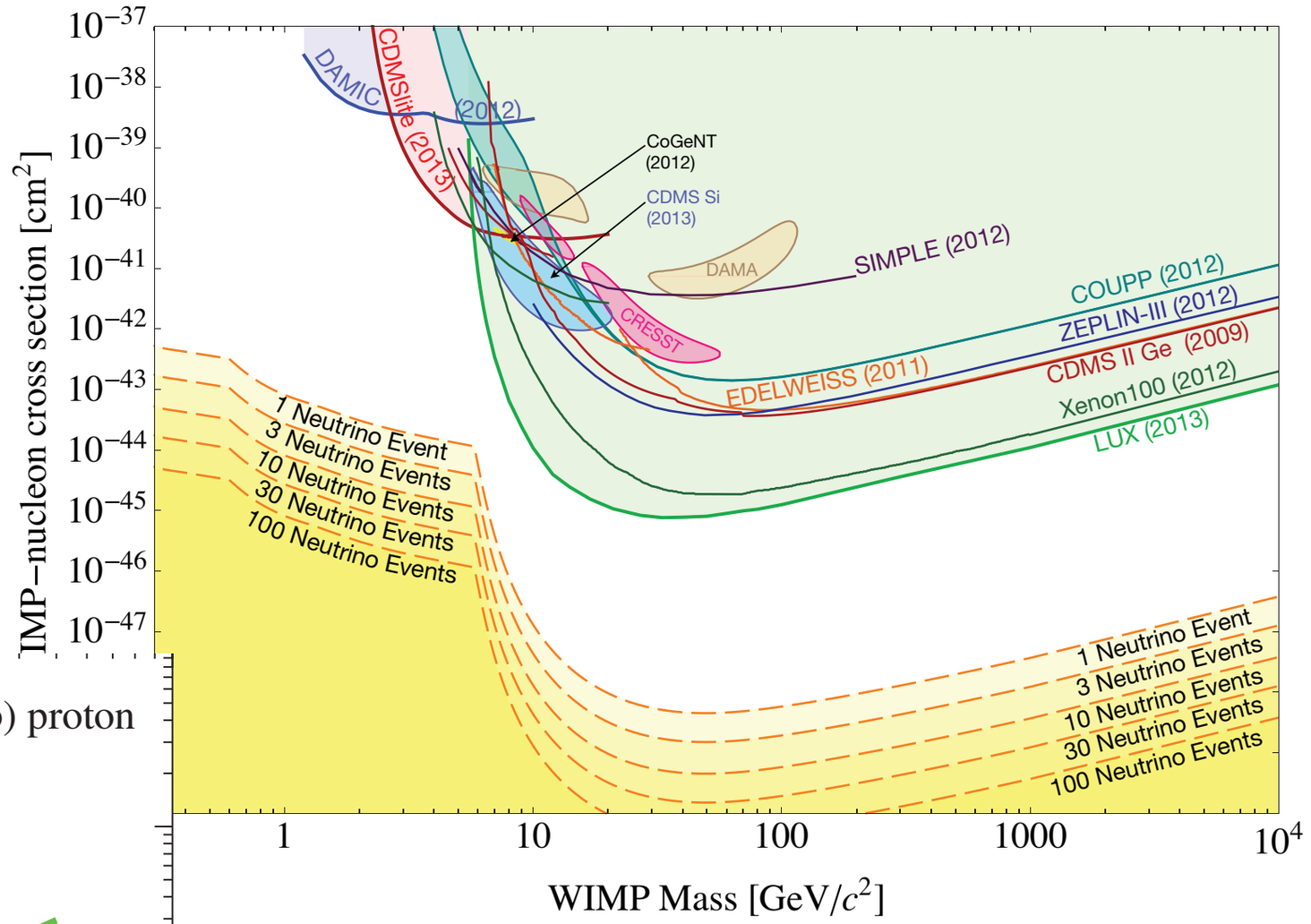
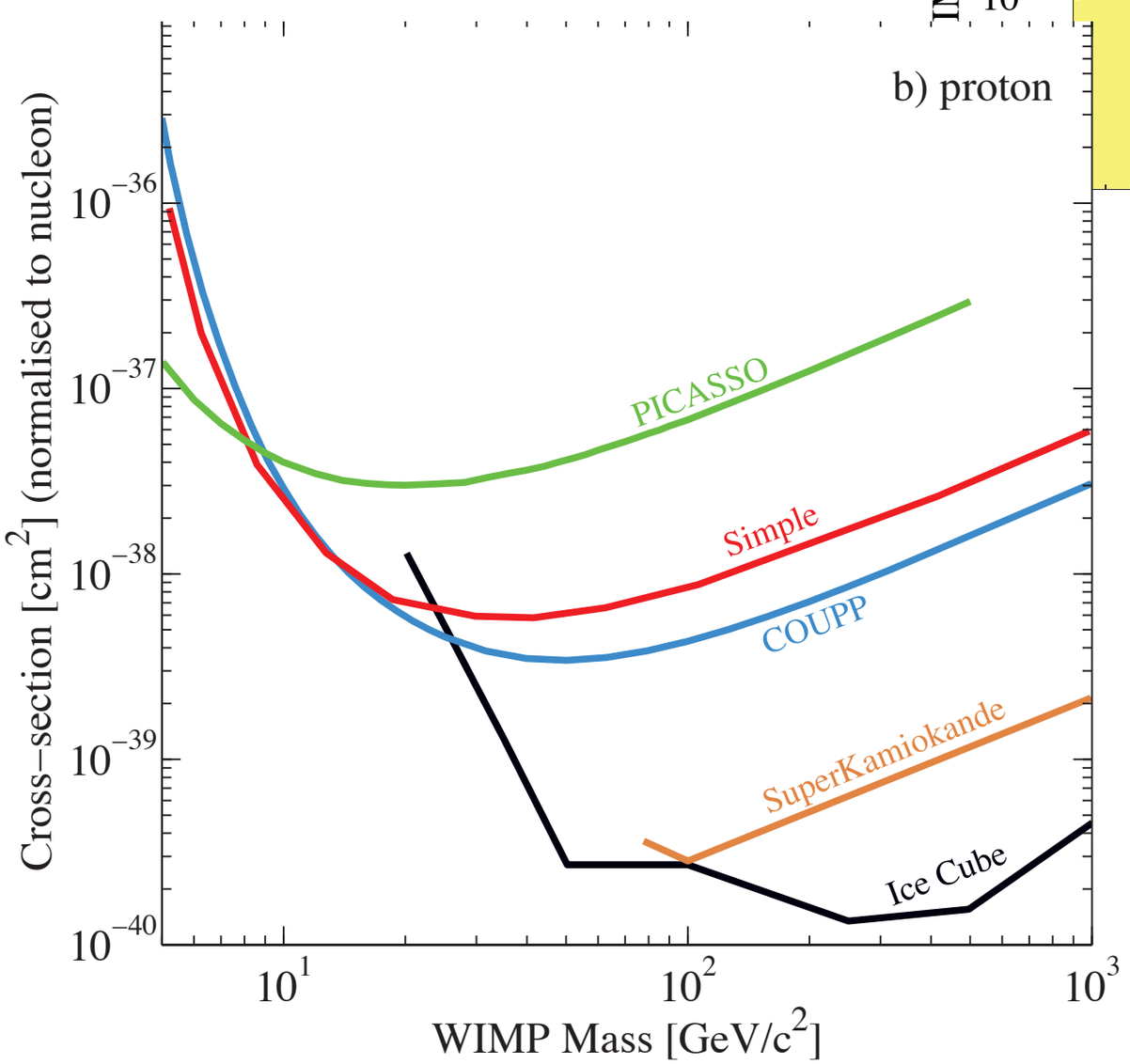
Z-exchange





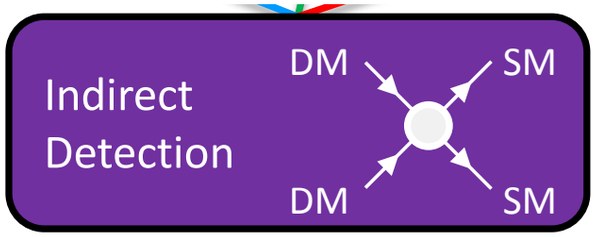




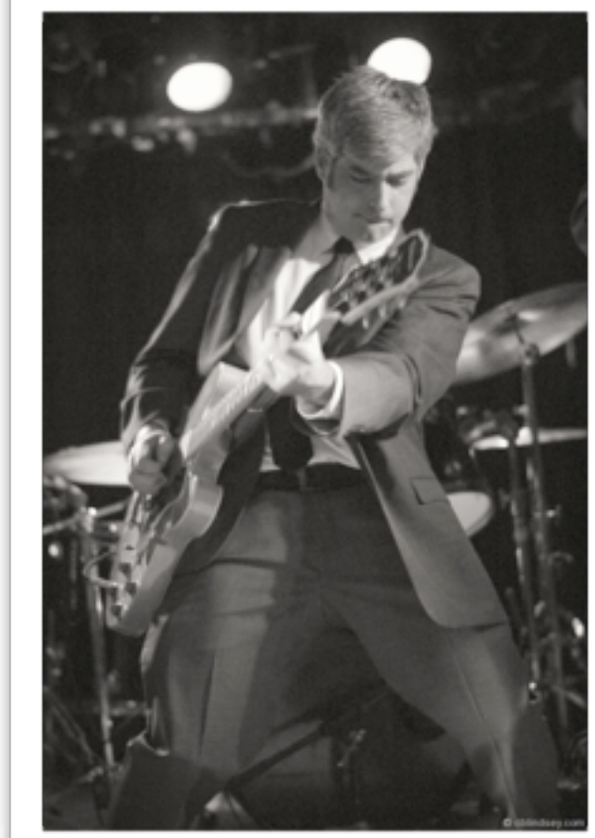
Some "hidden" assumptions:

- local density of DM is 0.3GeV/cm^3
- velocity distribution is MB
- scattering is elastic

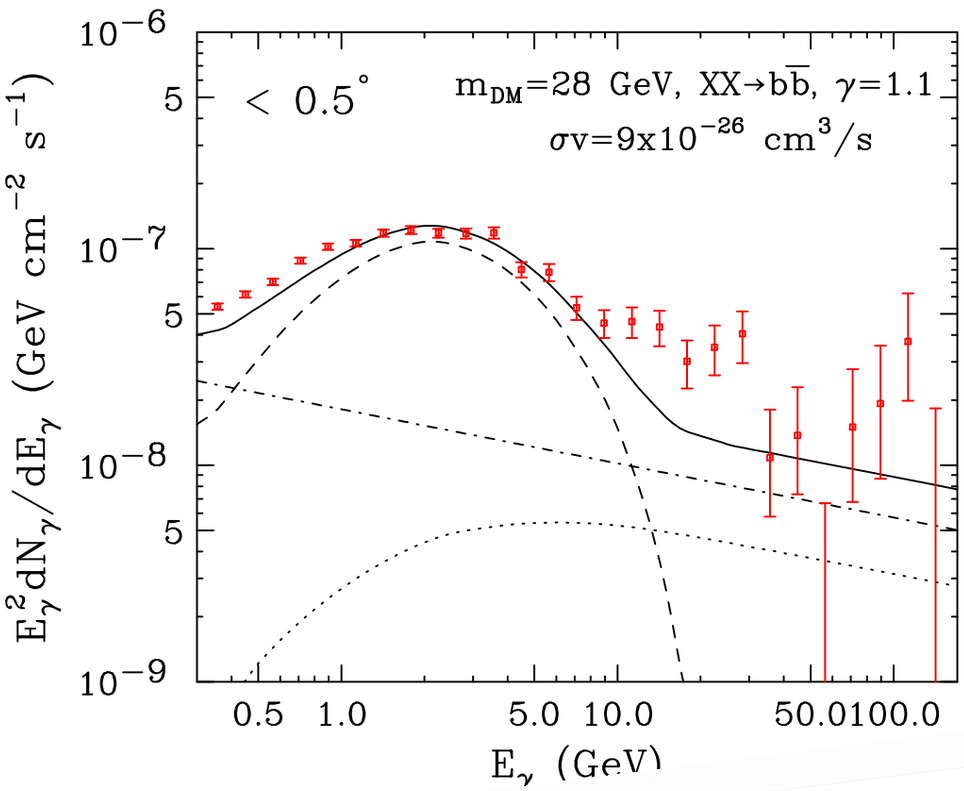
(see PF, Liu, Weiner for a way out of some of these problems)

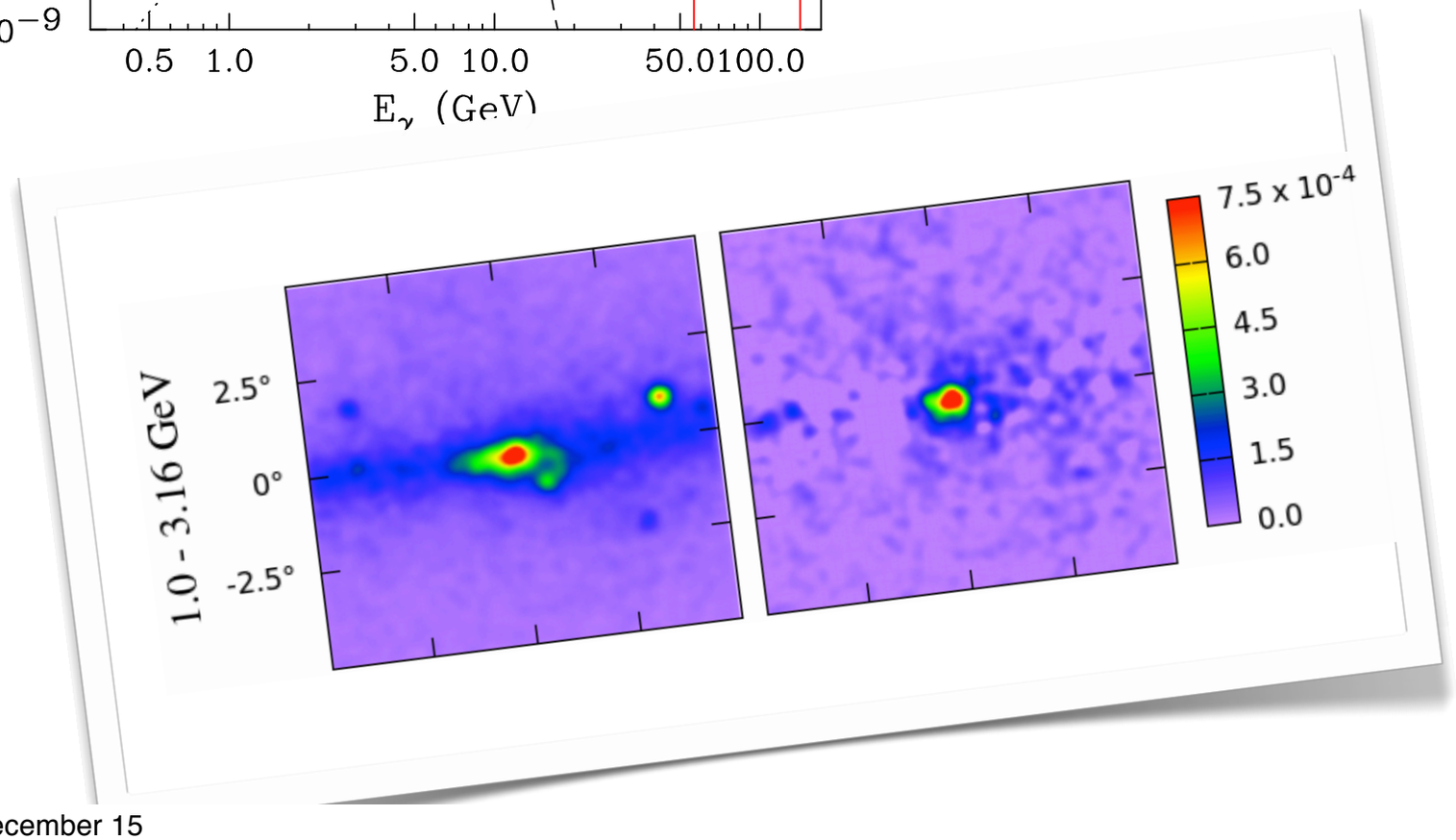


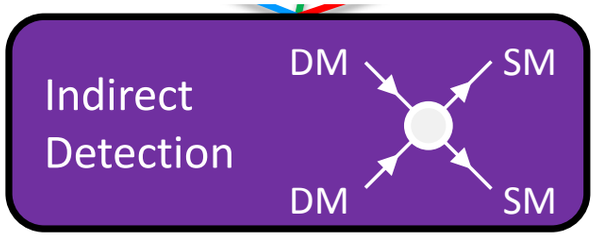
(See JiJi's and Alex's talks on Saturday)



[Goodenough and Hooper, 2009]







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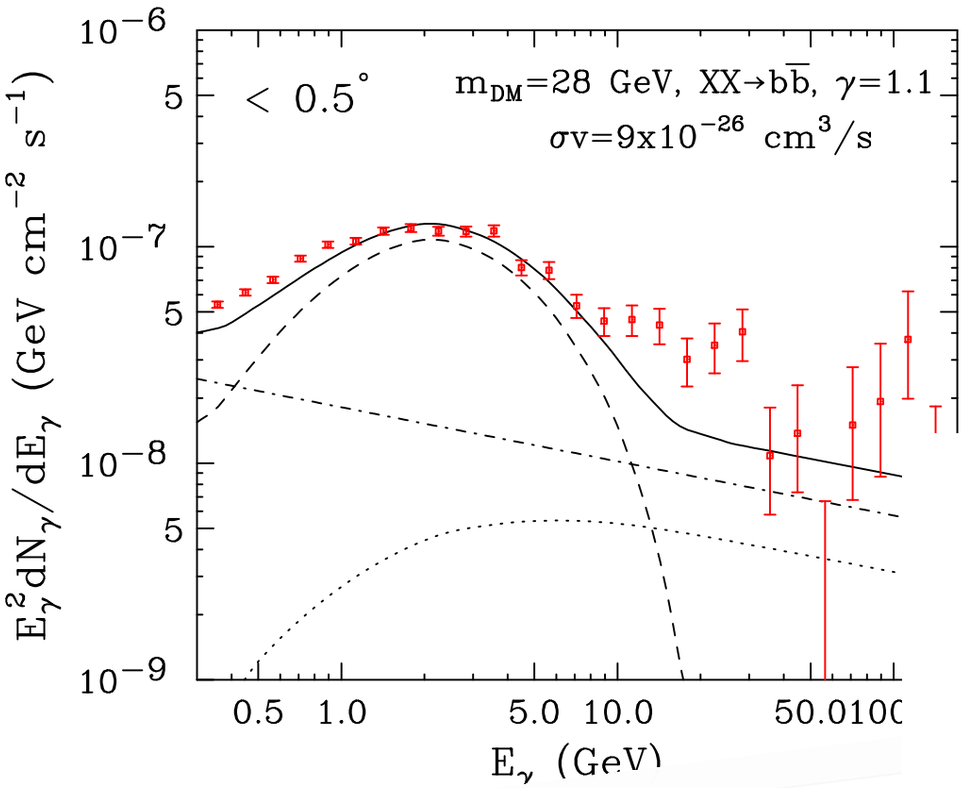
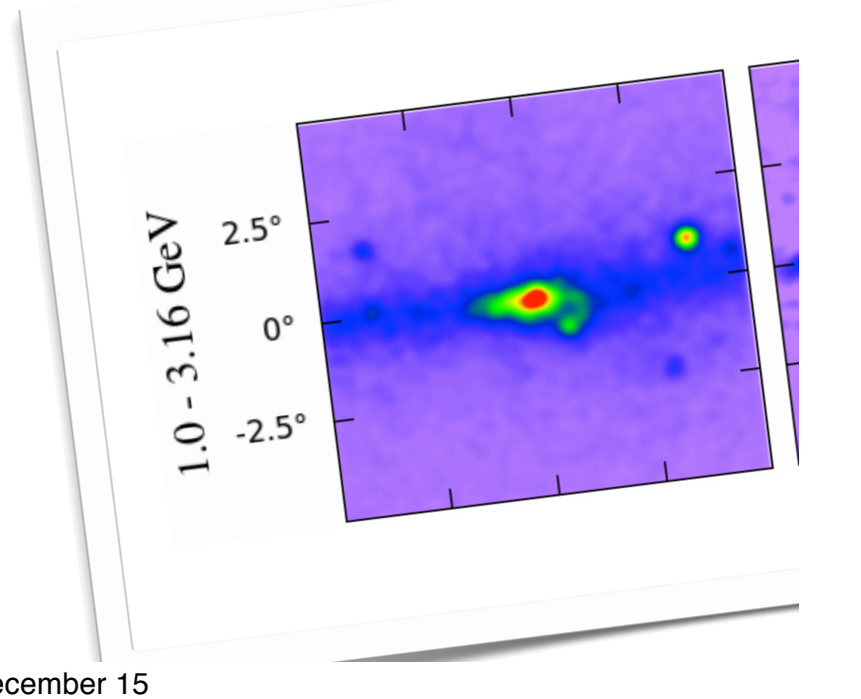
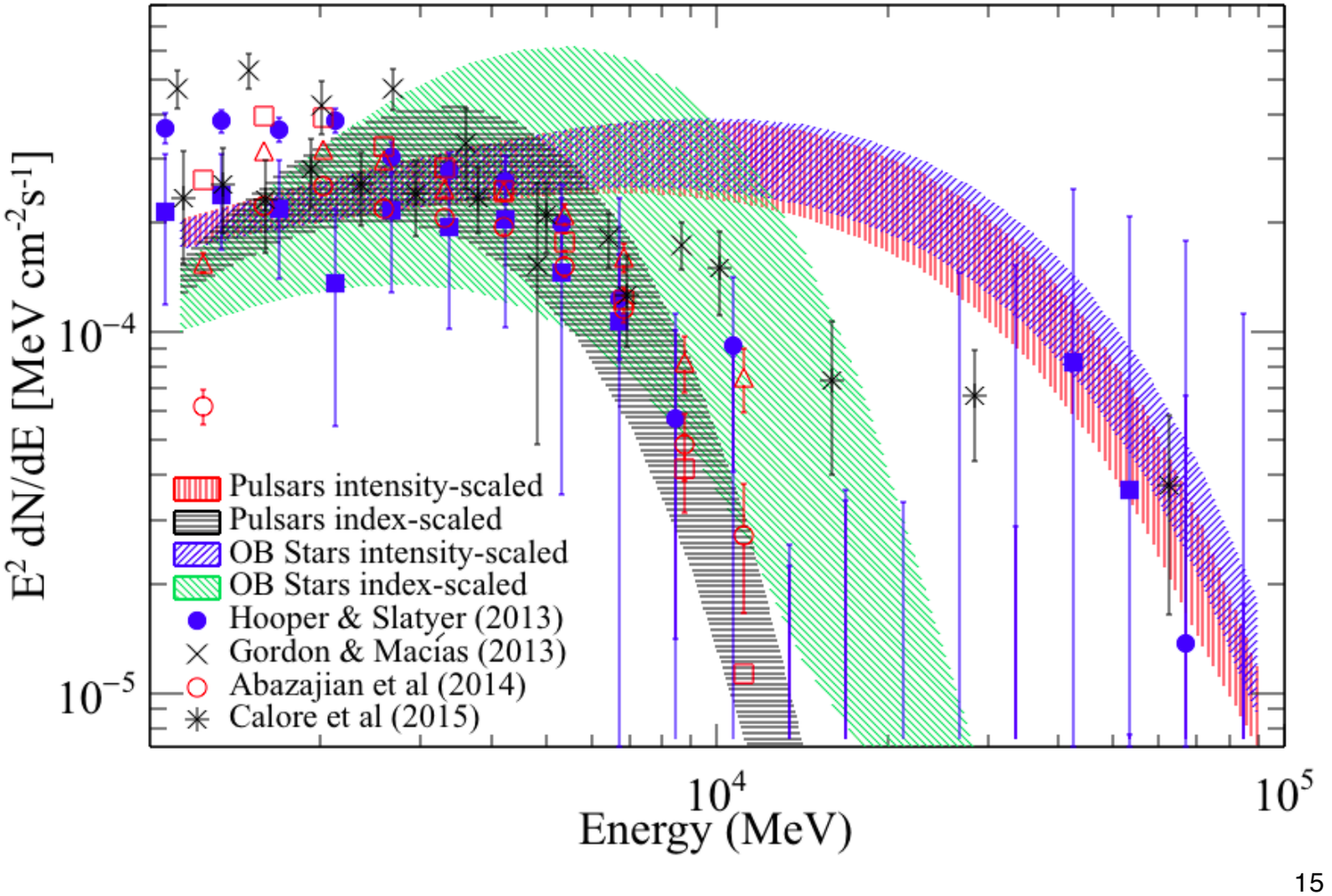




[Fermi (Simona Murgia)]

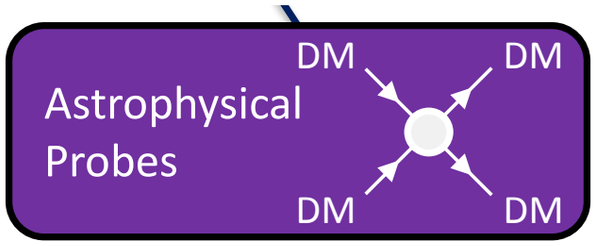


Are the excess photons from the Galactic centre DM?

- Source is spherical, with the expected radial dependence
- Cross section is close to thermal
- Centred in the right place
- Statistical significant, and Fermi-team sees it too

- Galactic centre is a confusing place
- Not as clear as a spectral line
- Milli-second pulsars (but we would have seen more, also spectrum different from those observed)

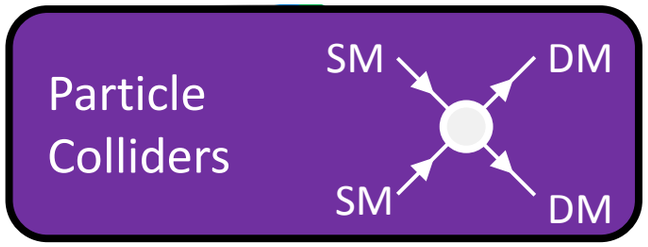
- Look at other DM "bright spots"--dwarf galaxies
- Cosmic ray anti-particles
- Correlated signals, LHC, direct detection
- **Interesting times ahead**



DM self interactions, probed by galaxies and galaxy clusters

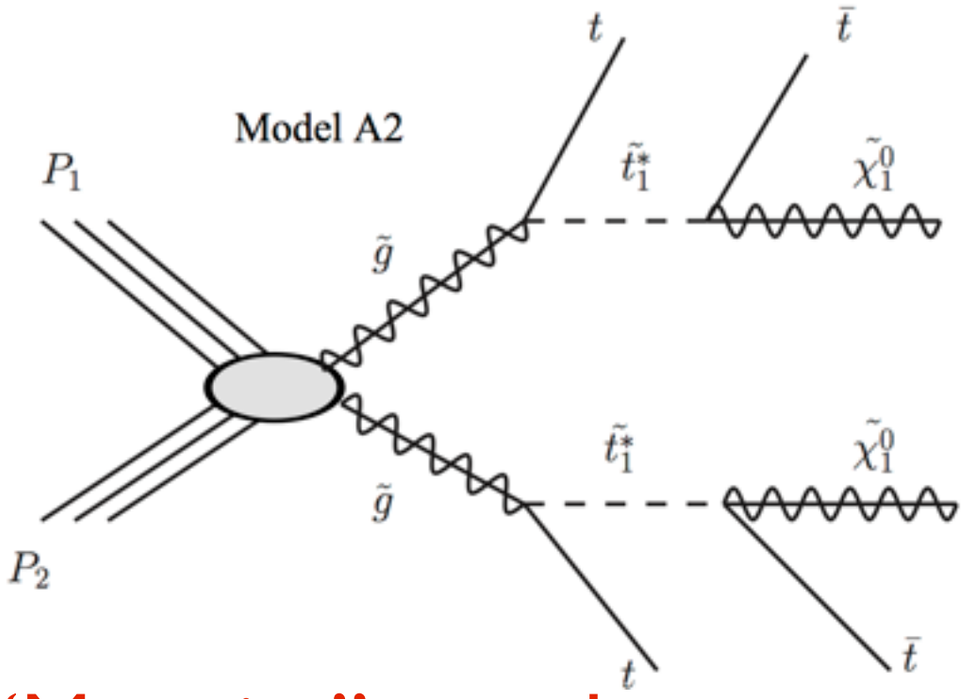
Help core-vs-cusp, missing satellite and too big to fail problems?

Light mediators give velocity dependence, need simulations



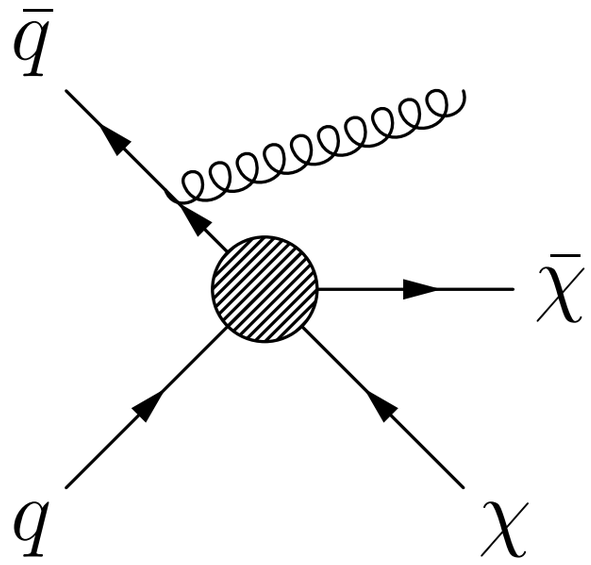
- Collider stable = cosmologically stable?
- No astrophysical assumptions
- Limited by kinematic reach

"Traditional" searches

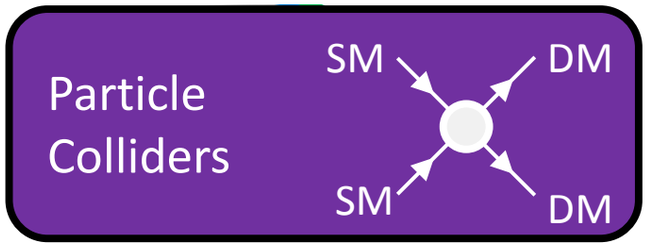


- Many models with DM (e.g. SUSY), searches are model specific
- Many kinematic quantities

"Monojet" searches



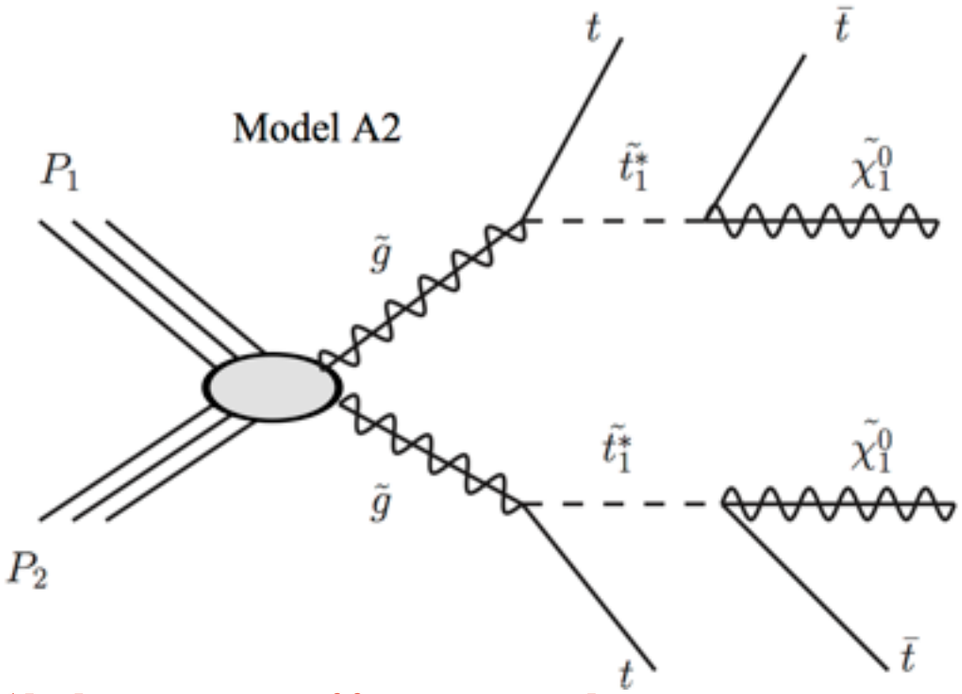
- Only search for DM, "model independent"
- Direct link to direct detection
- Few kinematic quantities



- Collider st… …stable?
- No ast…
- Limited…

(see e.g. Oliver, James, Joe, and many other talks in workshop)

"Traditional" searches



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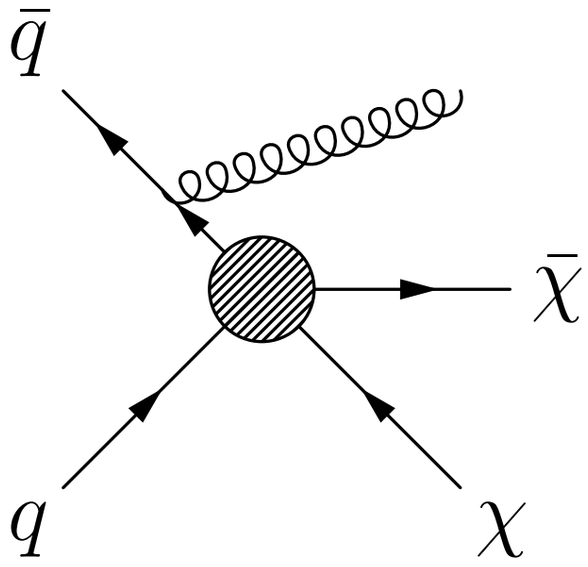

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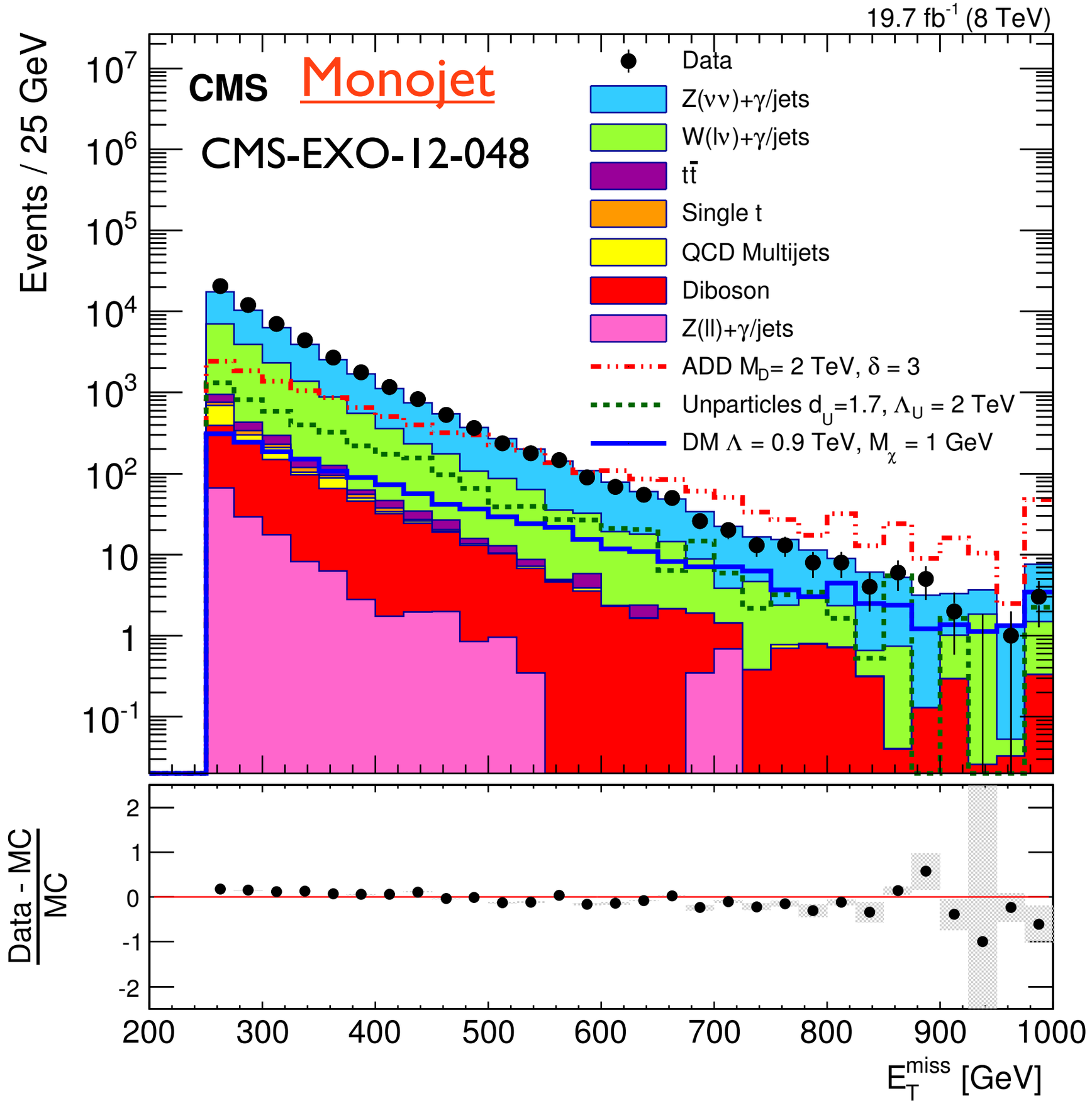
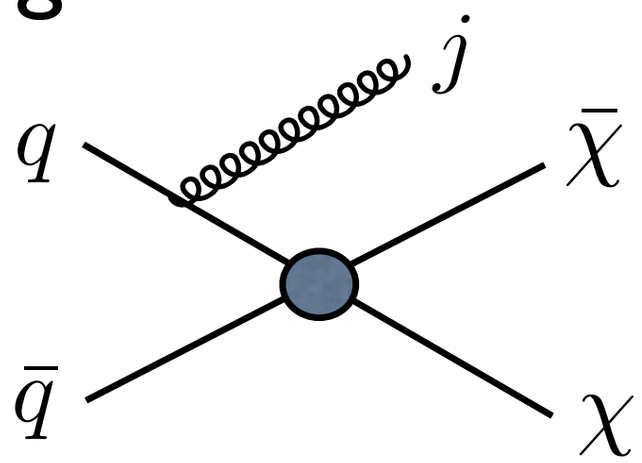
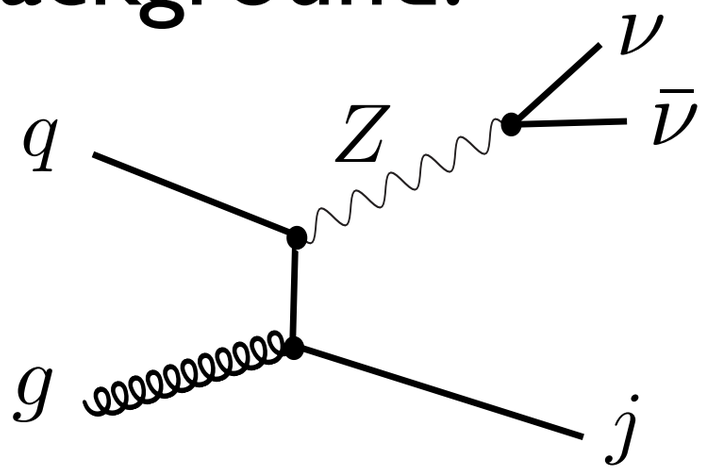


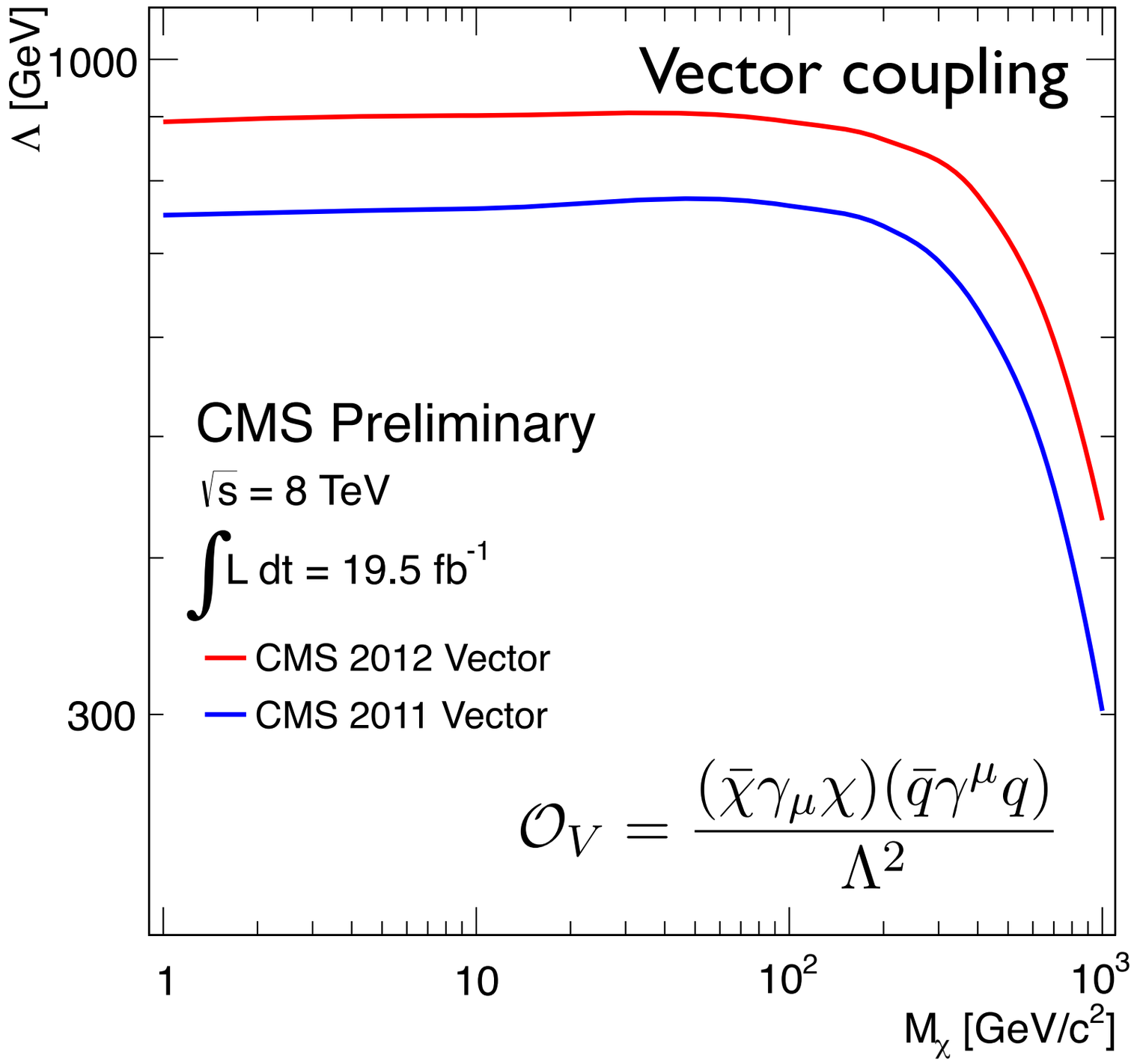
Signal:



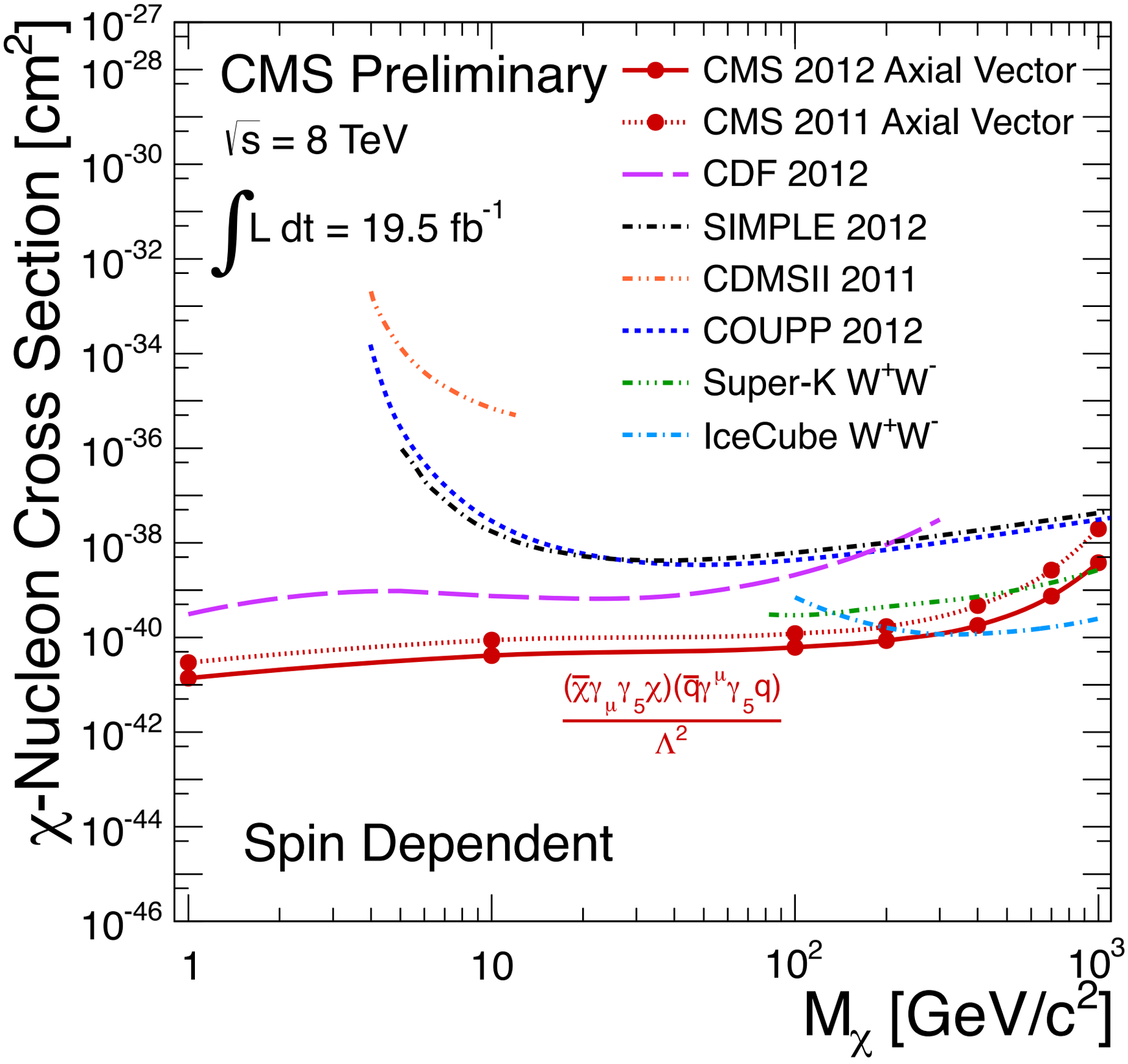
(Dominant) Background:



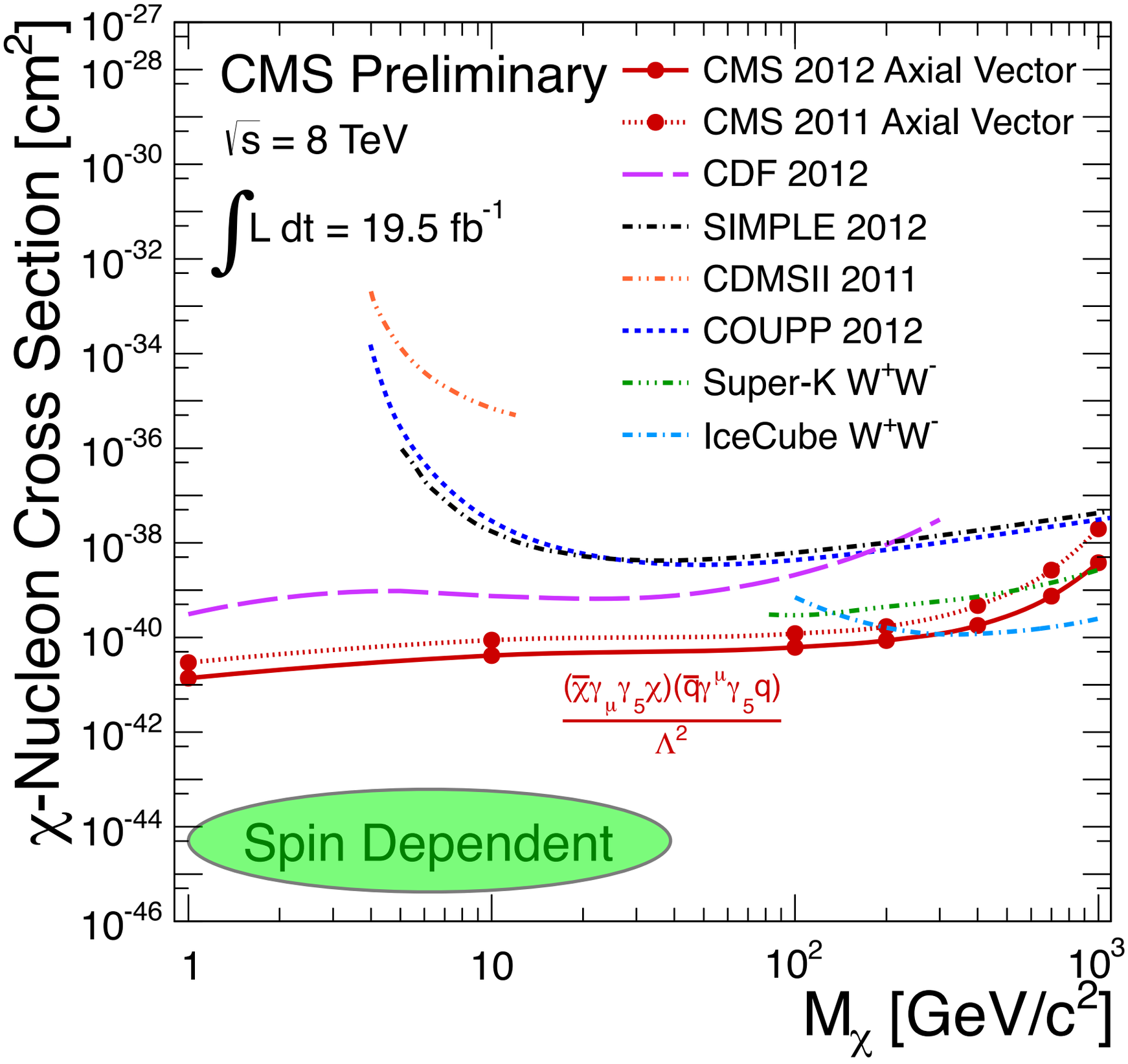
How to quantify nothing?



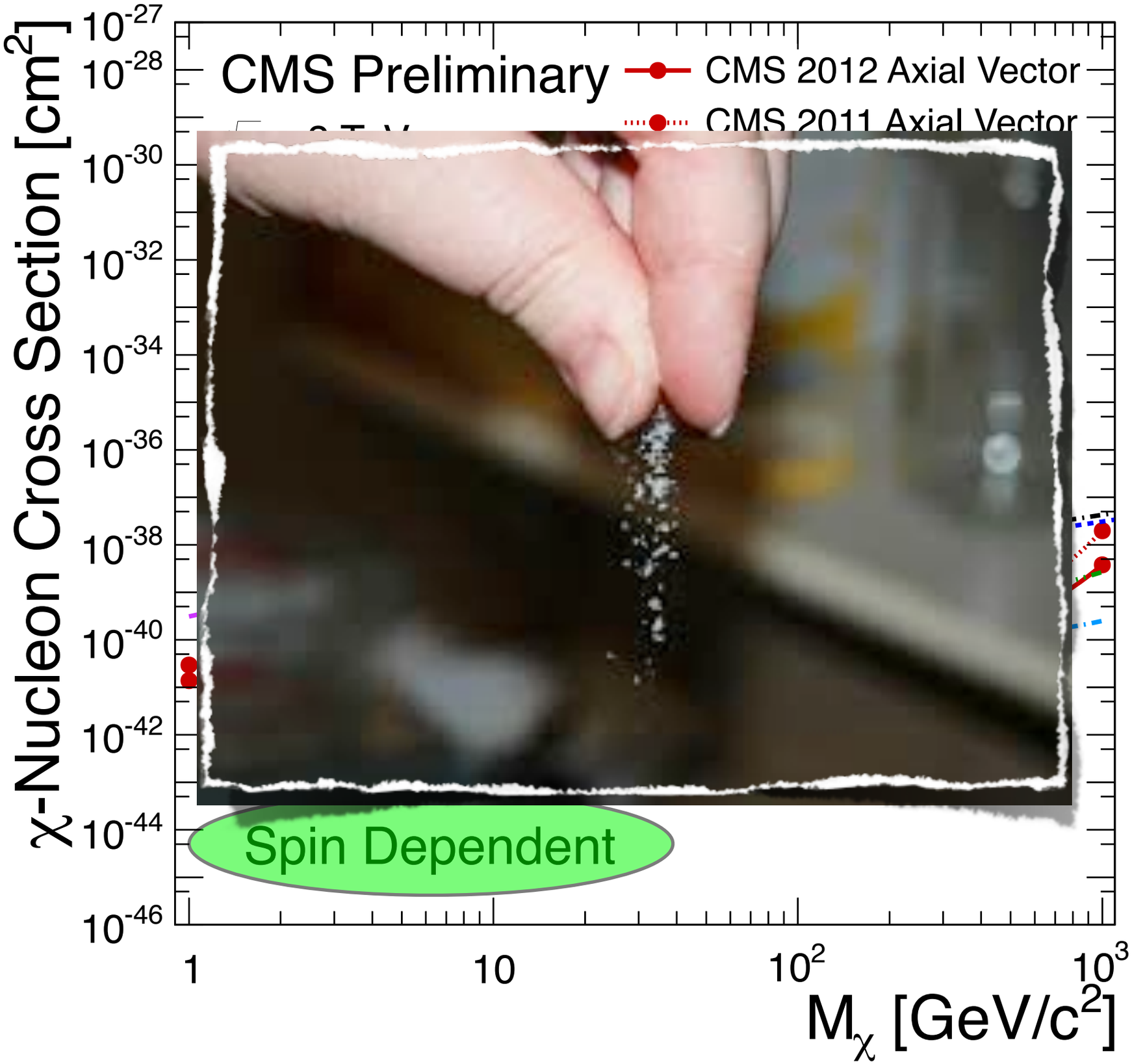
Monojet


CMS Preliminary
√s = 8 TeV
∫L dt = 19.5 fb-1
CMS 2012 Axial Vector
CMS 2011 Axial Vector
CDF 2012
SIMPLE 2012
CDMSII 2011
COUPP 2012
Super-K W+W-
IceCube W+W-
(χ̄γμγ5χ)(q̄γμγ5q) / Λ2
Spin Dependent
χ-Nucleon Cross Section [cm2]
Mχ [GeV/c2]
10-27
10-28
10-30
10-32
10-34
10-36
10-38
10-40
10-42
10-44
10-46
1
10
10²
10³

Monojet


CMS Preliminary
√s = 8 TeV
∫L dt = 19.5 fb-1
CMS 2012 Axial Vector
CMS 2011 Axial Vector
CDF 2012
SIMPLE 2012
CDMSII 2011
COUPP 2012
Super-K W+W-
IceCube W+W-
(χ̄γμγ5χ)(q̄γμγ5q) / Λ2
Spin Dependent
χ-Nucleon Cross Section [cm2]
Mχ [GeV/c2]
10-27
10-28
10-30
10-32
10-34
10-36
10-38
10-40
10-42
10-44
10-46
1
10
10²
10³

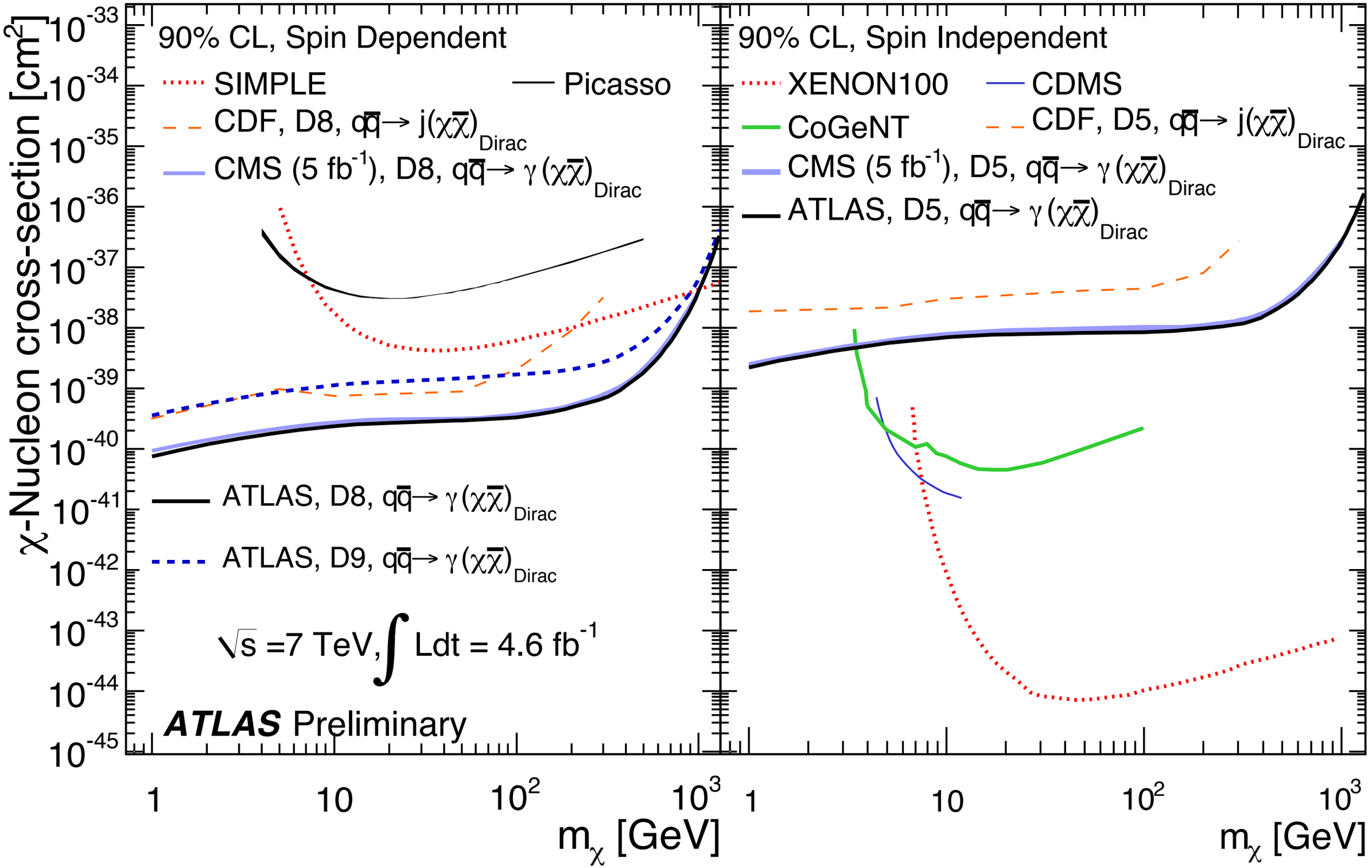
Monojet


CMS Preliminary
CMS 2012 Axial Vector
CMS 2011 Axial Vector
Spin Dependent
χ-Nucleon Cross Section [cm²]
10^-27
10^-28
10^-30
10^-32
10^-34
10^-36
10^-38
10^-40
10^-42
10^-44
10^-46
1
10
10^2
10^3
M_χ [GeV/c²]

Monophoton

$$D8 = \bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma^{\mu}\gamma_5 q$$

$$D5 = \bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma^{\mu}q$$



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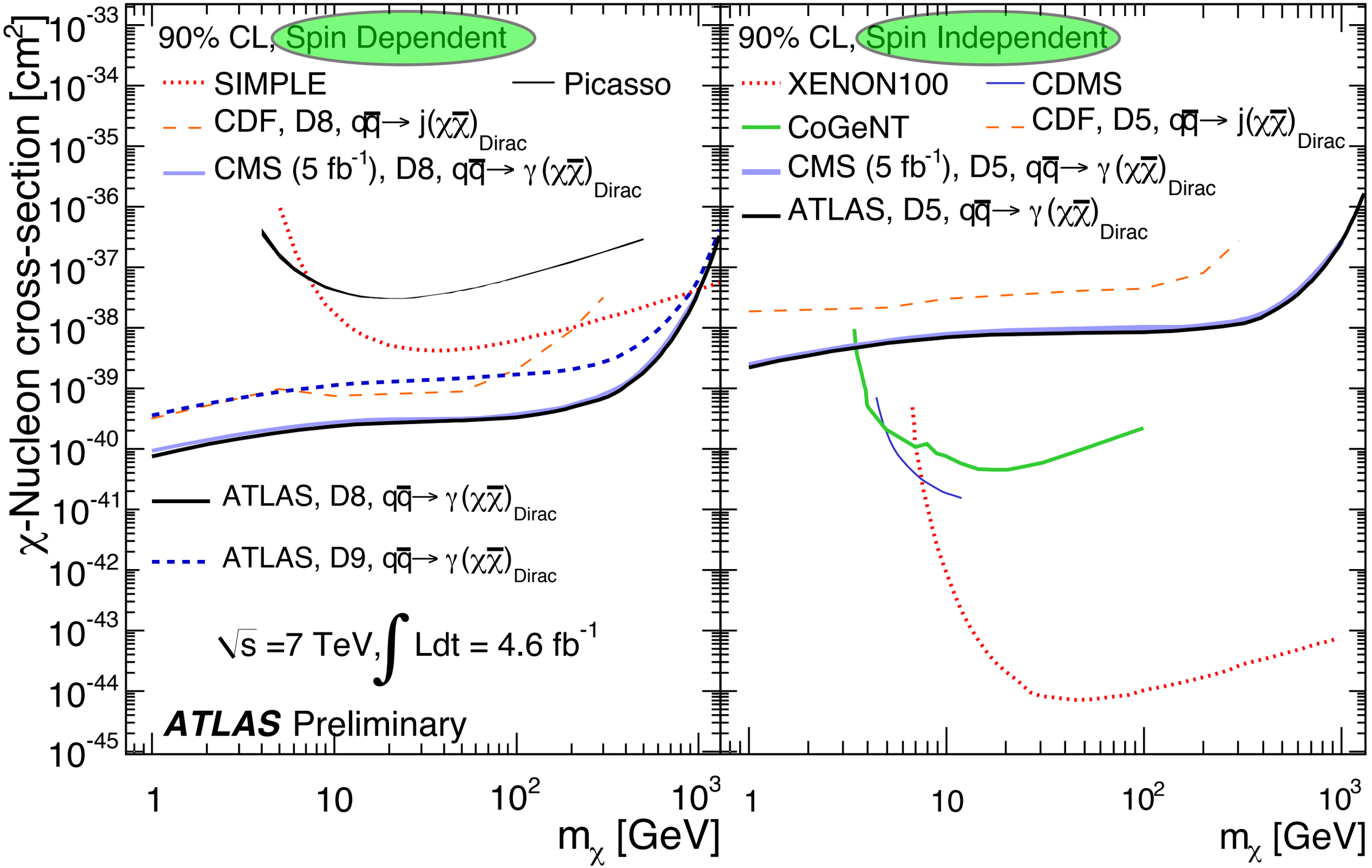


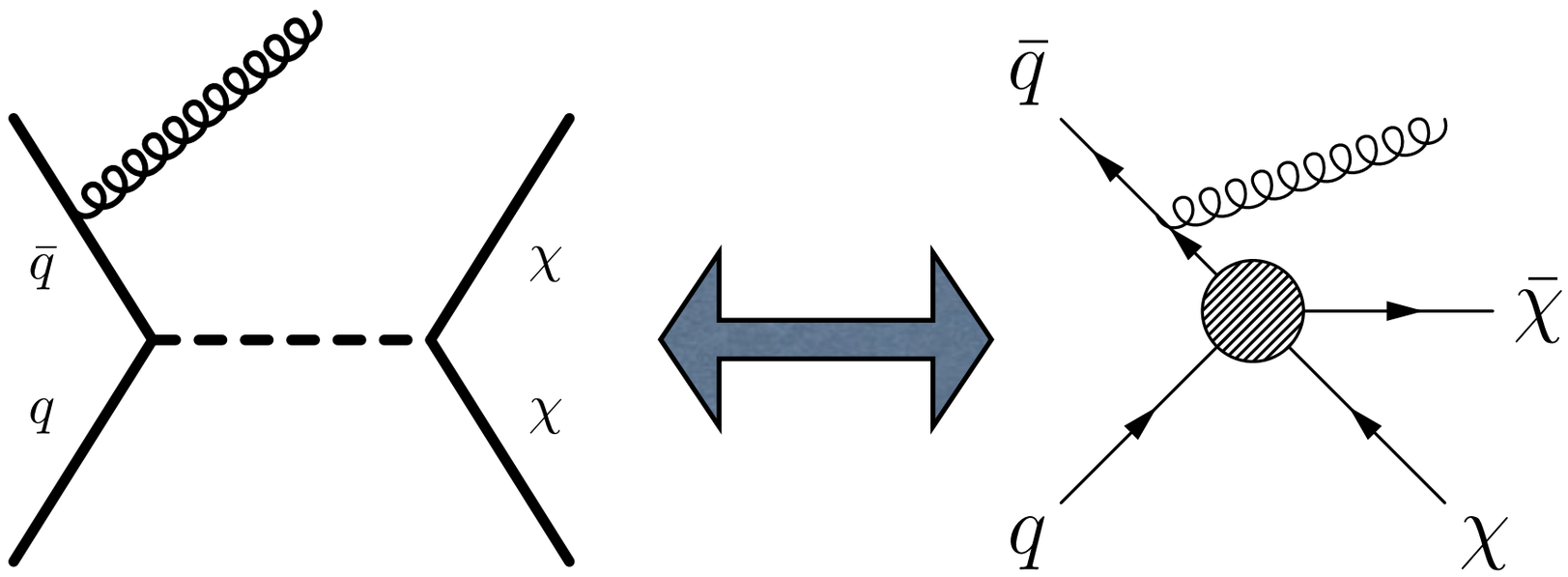
Mono-mania at the LHC

Light Mediators & Dressing up the EFT

For all but the lightest mediators EFT is good for direct detection

$$\sigma(\chi N \to \chi N) \sim \frac{g_q^2 g_\chi^2}{M^4} \mu_{\chi N}^2$$

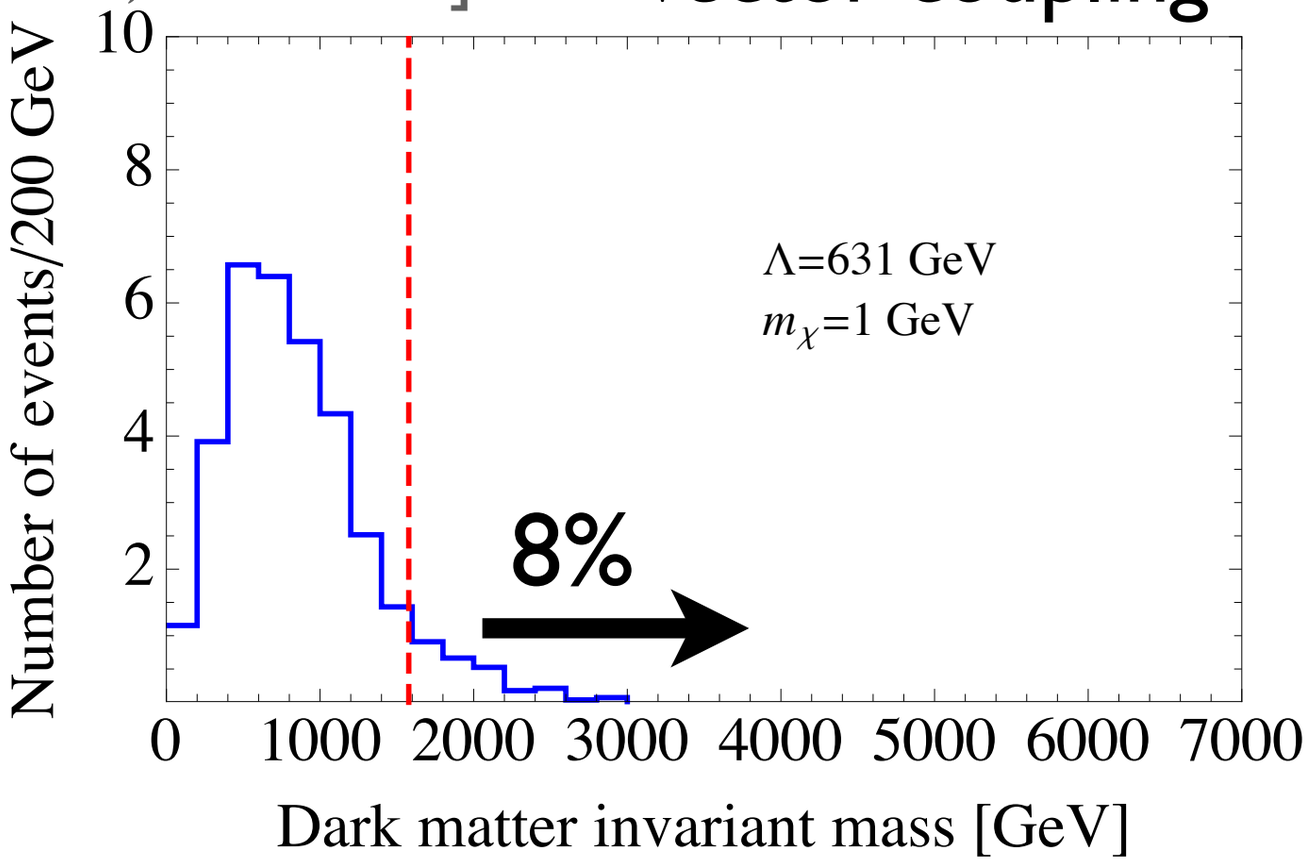
What fraction of collider events have momentum transfers sufficient to probe the UV completion?



$$\frac{g_q g_\chi}{q^2 - M^2} \xrightarrow{q^2 \ll M^2} \frac{1}{\Lambda^2} \qquad \Lambda^2 = \frac{M^2}{g_q g_\chi}$$

[PF et al, 1203.1662]

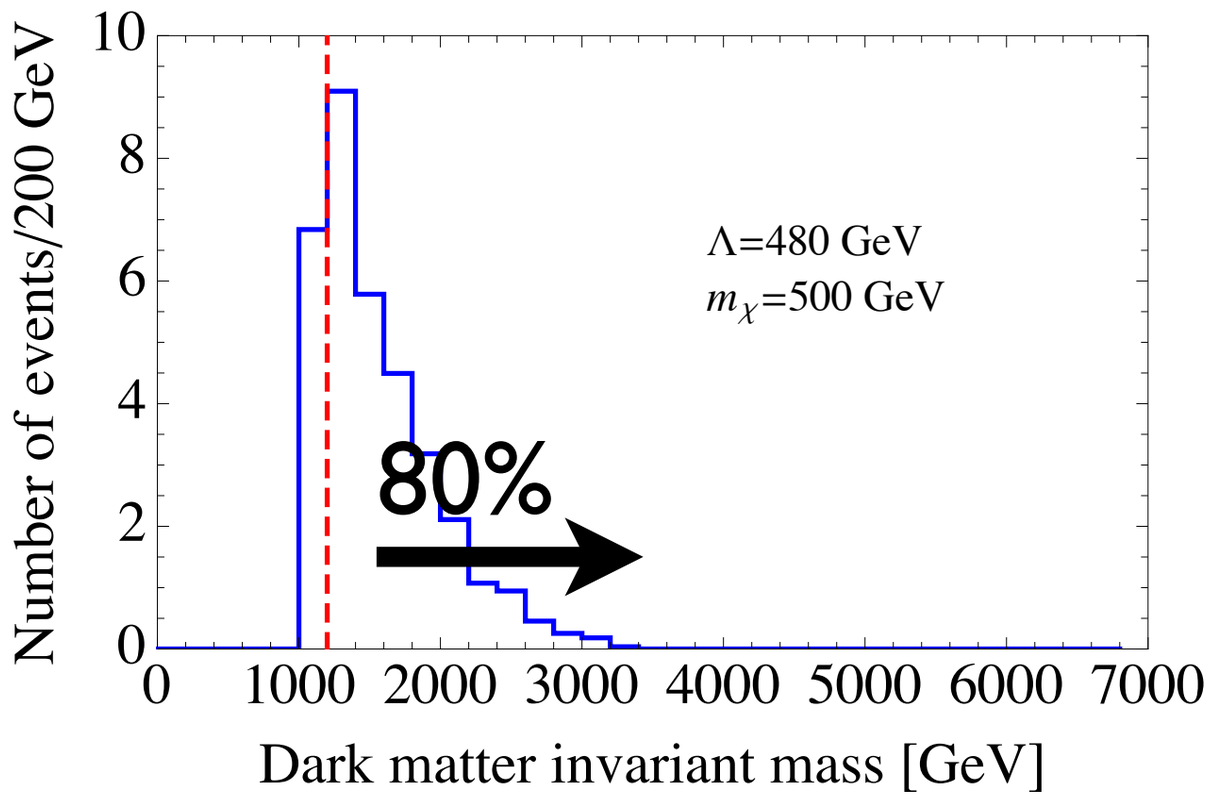
Vector coupling



Unitarity bound $m_{\chi\chi} < \frac{\Lambda}{0.4}$

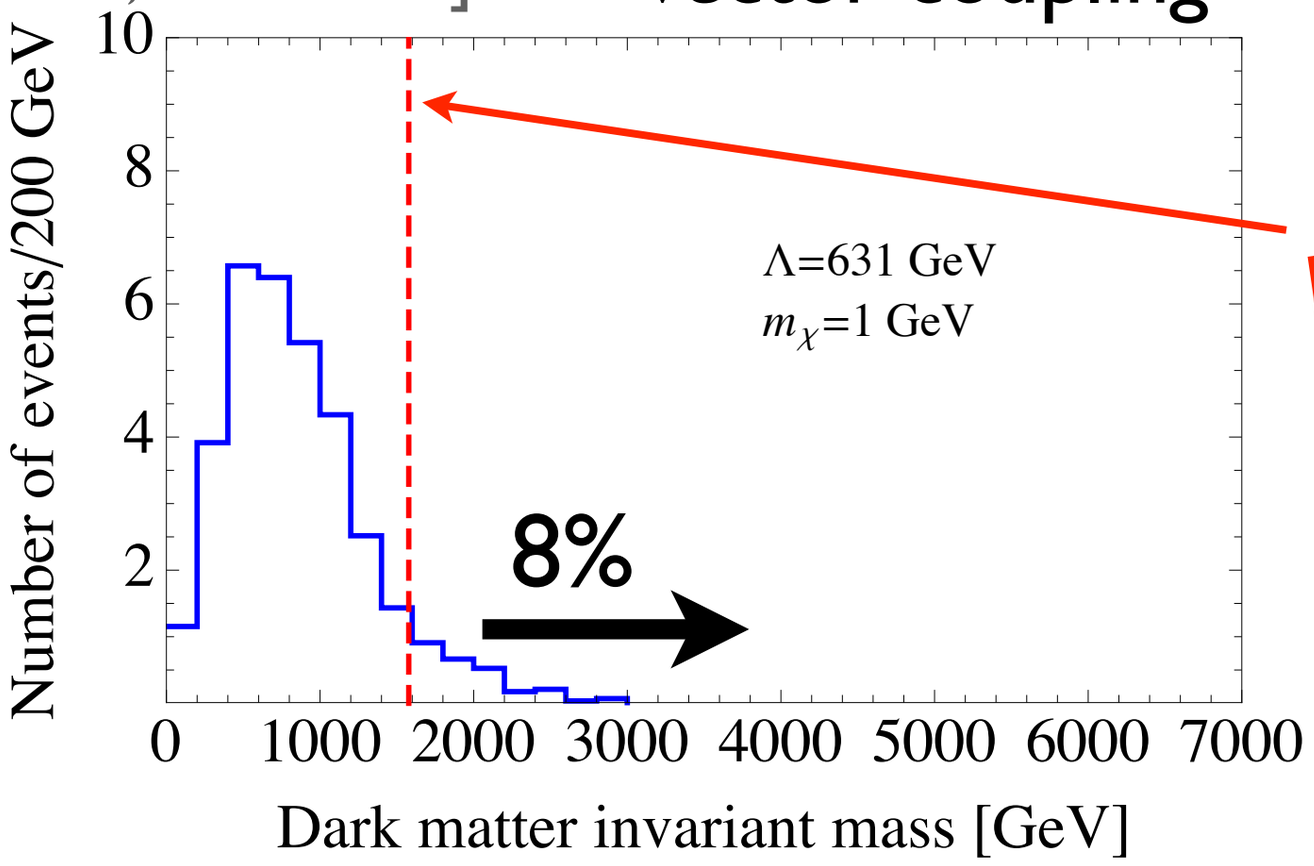
[Shoemaker and Vecchi, 1112.5457]

Fraction of events where EFT breaks down may be non-negligible
Depends on DM mass



[PF et al, 1203.1662]

Vector coupling



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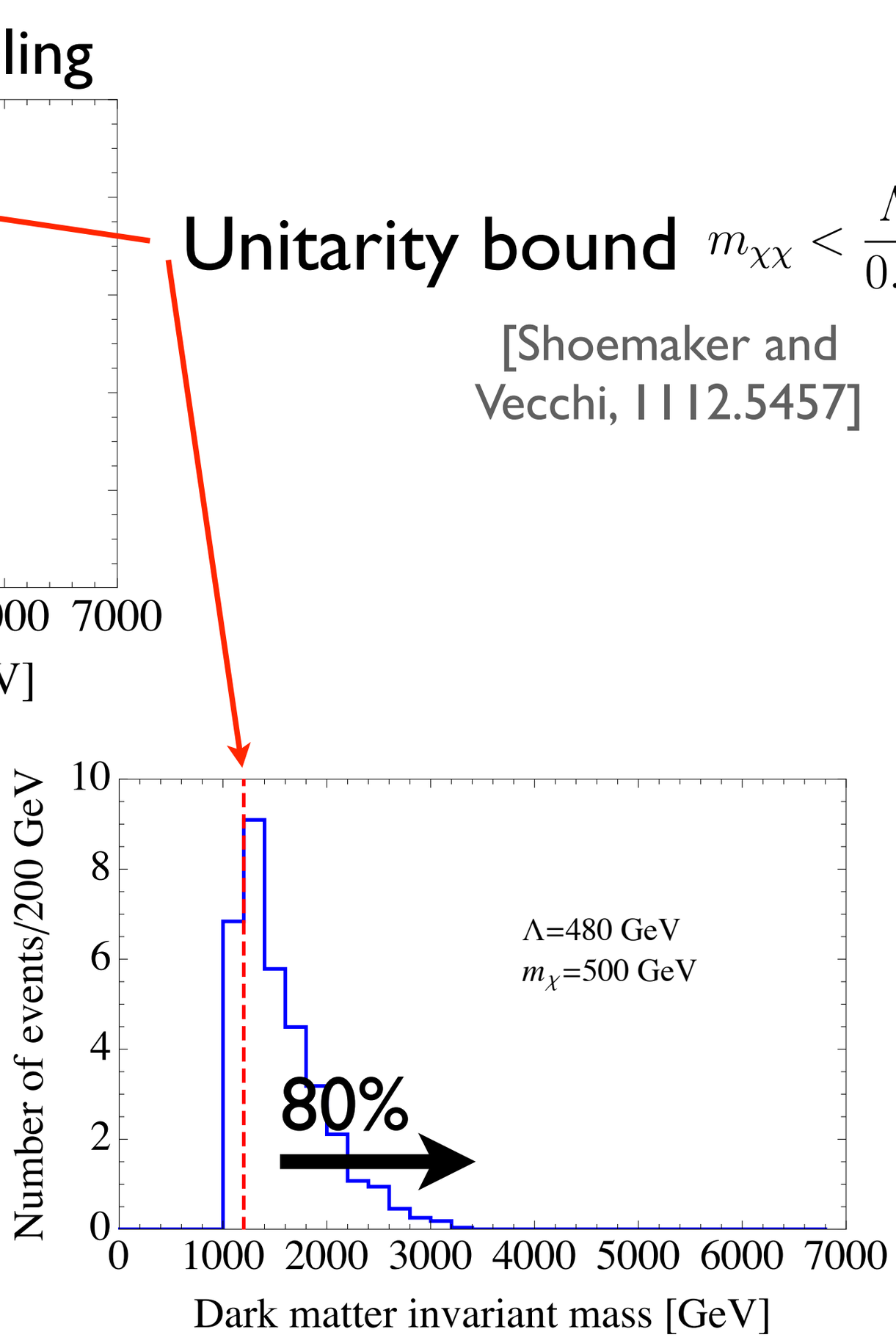

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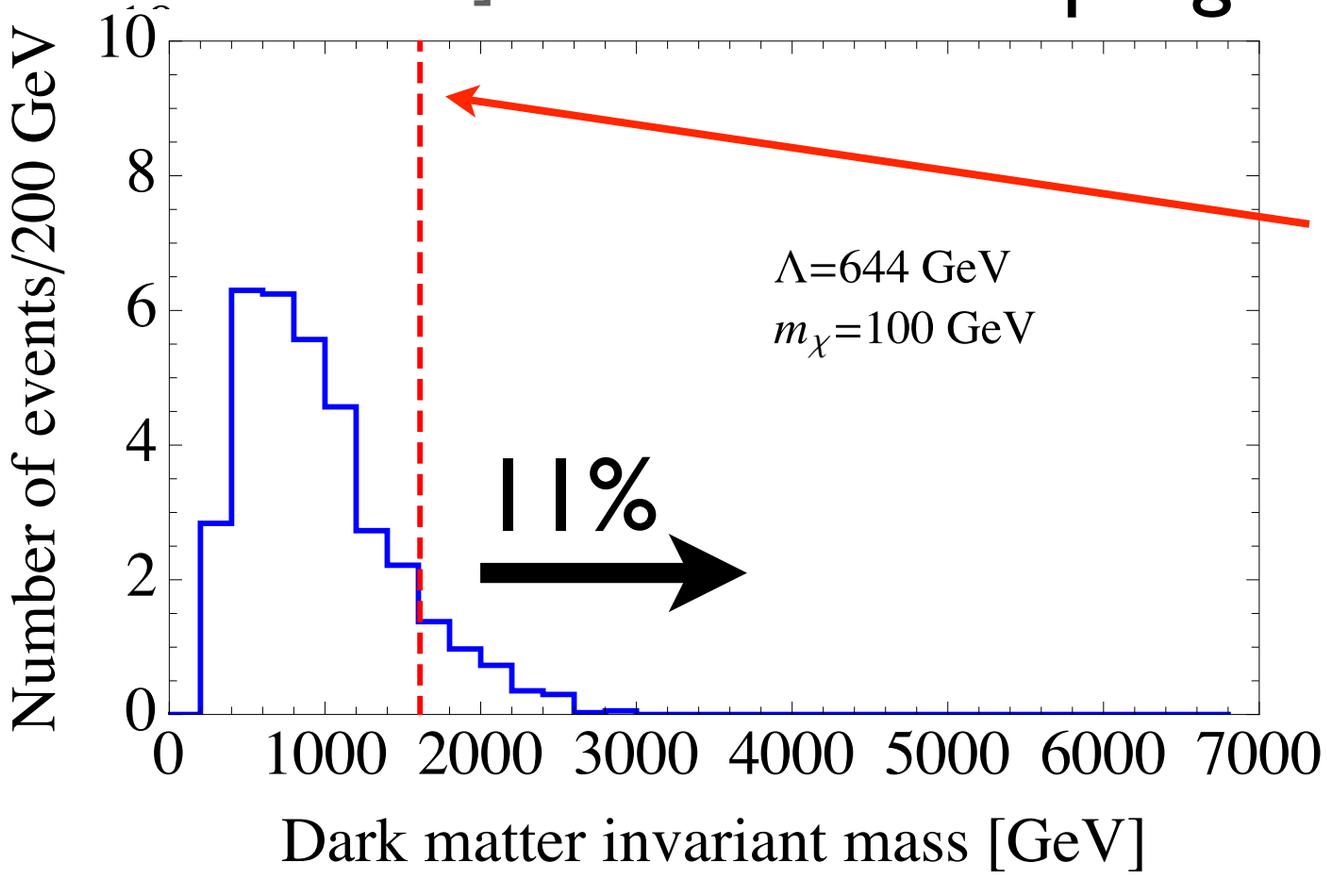
Vector coupling



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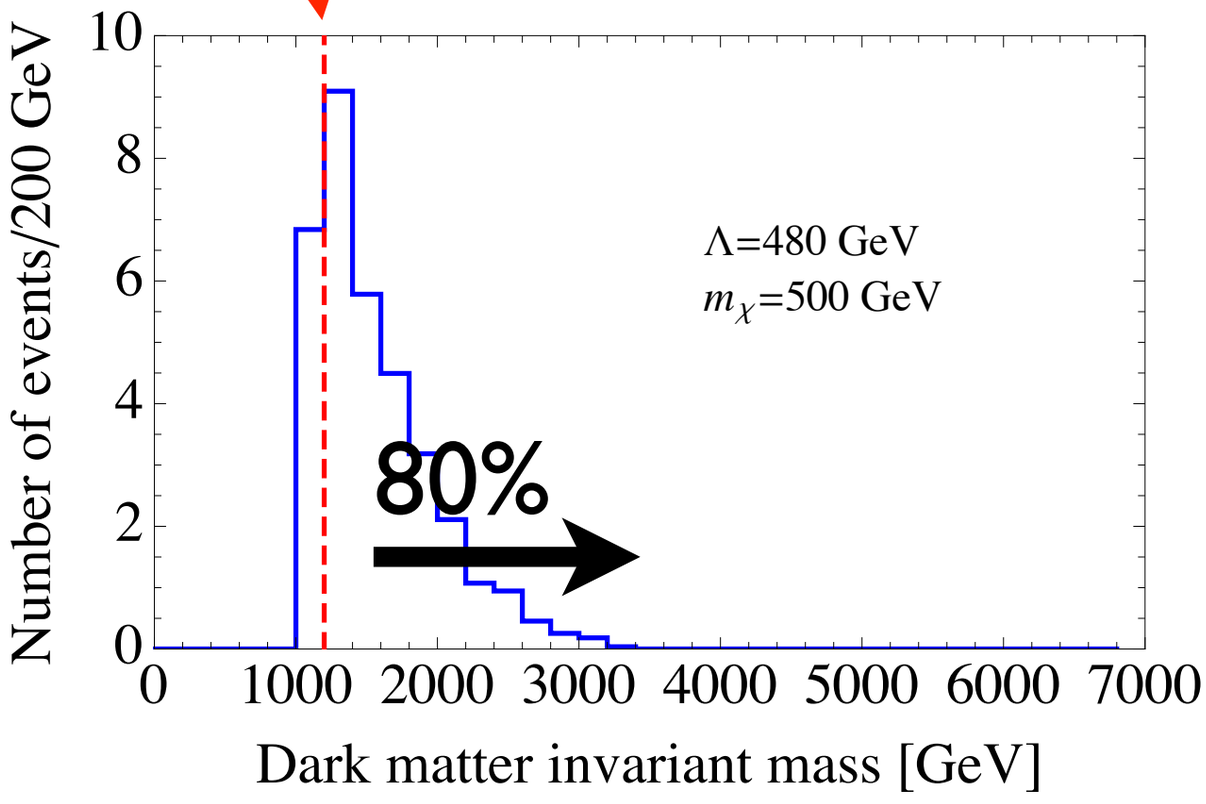
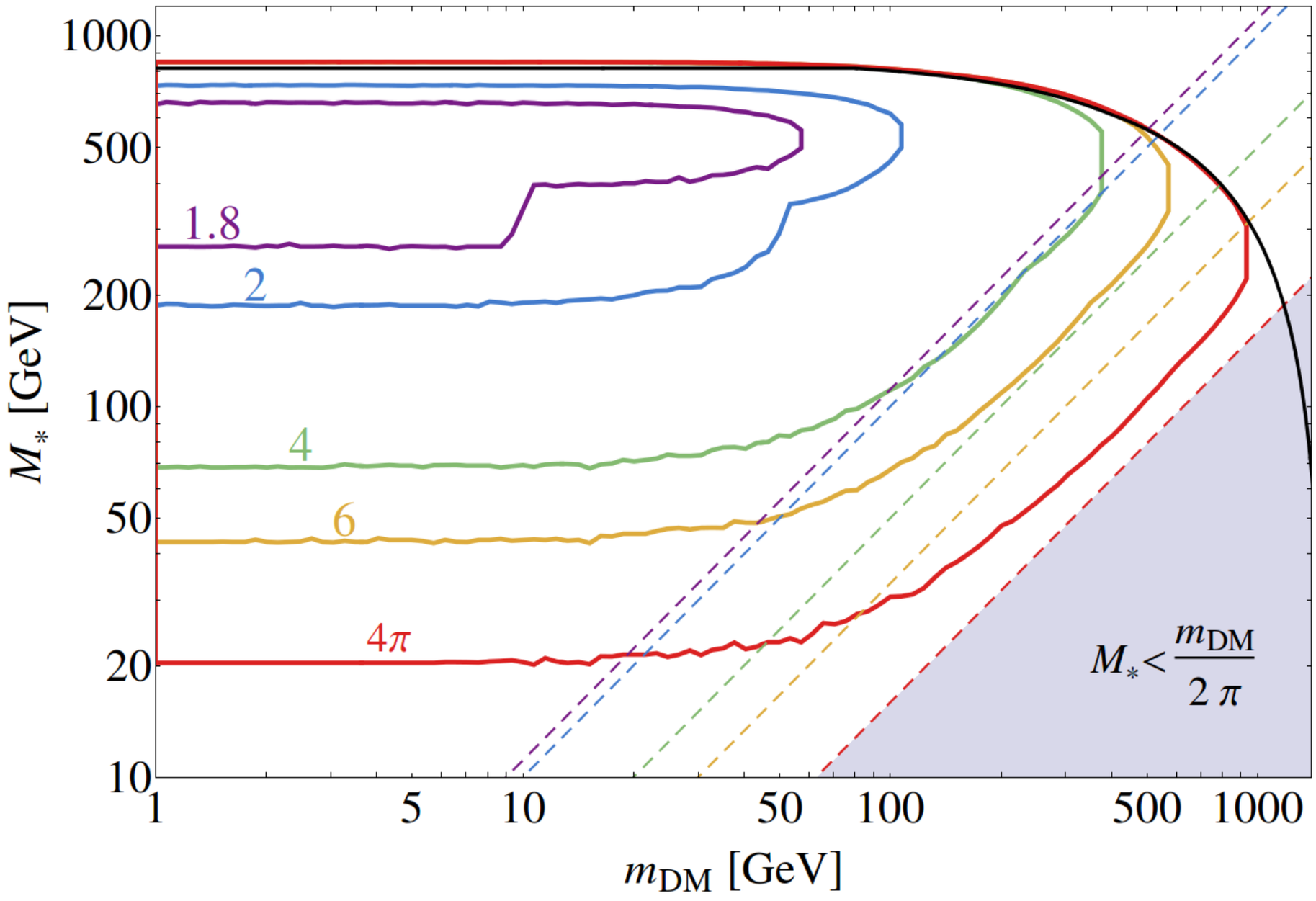


Fraction of events where EFT breaks down may be non-negligible

Depends on DM mass

[Racco, Wulzer, Zwirner, 1502.04701]

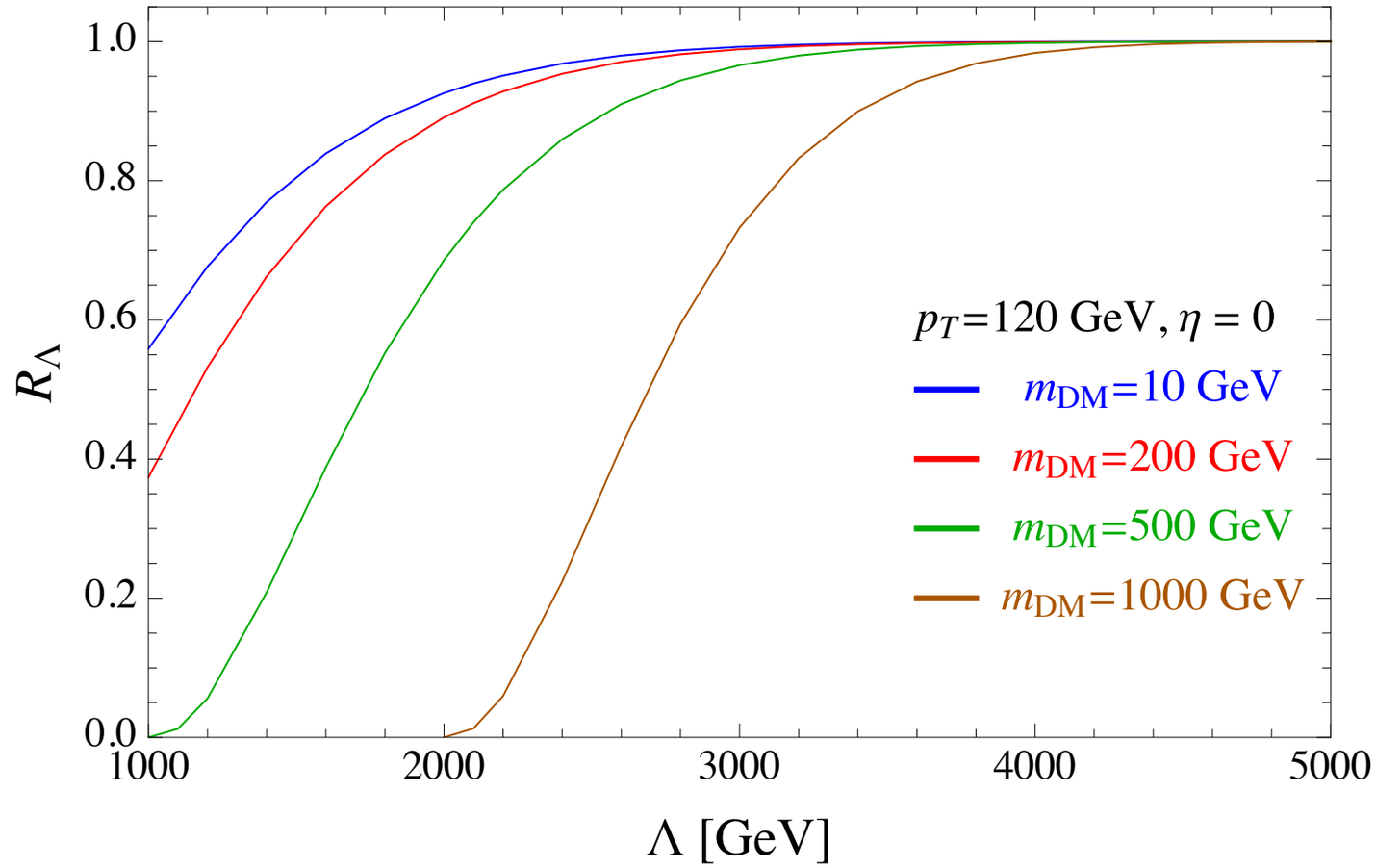
Require that $E_{cm} < M_{cut} = g\Lambda$



What fraction of events have momentum transfers sufficient to probe the UV completion?

[Busoni, De Simone, Morgante, Riotto, 1307.2253, 1402.1275, 1405.3103]

$$R_\Lambda \equiv \frac{\left.\frac{\mathrm{d}^2\sigma_{\mathrm{eff}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}\right|_{Q_{\mathrm{tr}}<\Lambda}}{\frac{\mathrm{d}^2\sigma_{\mathrm{eff}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}}$$



$$\frac{g^2}{M^2} = \frac{1}{\Lambda^2}$$

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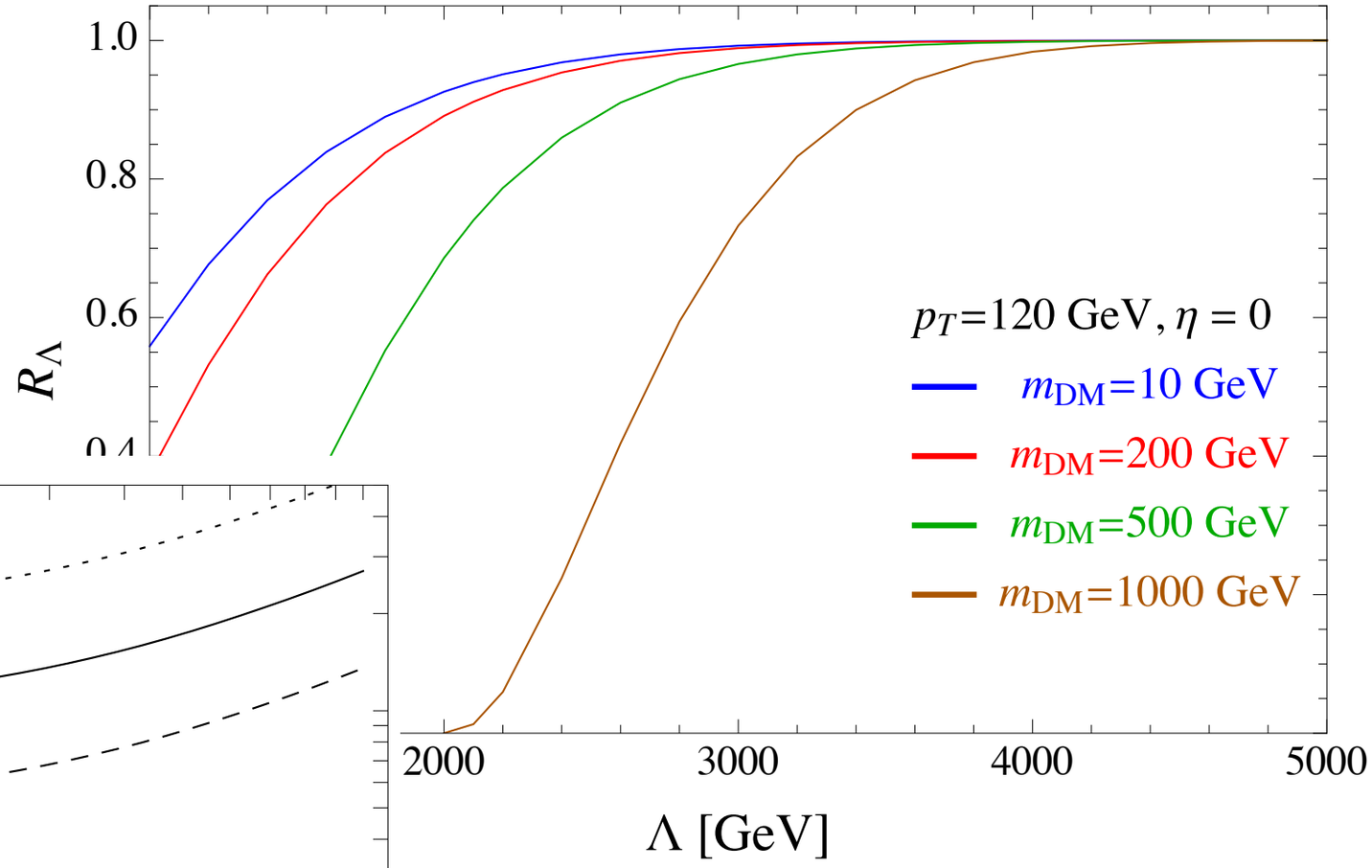
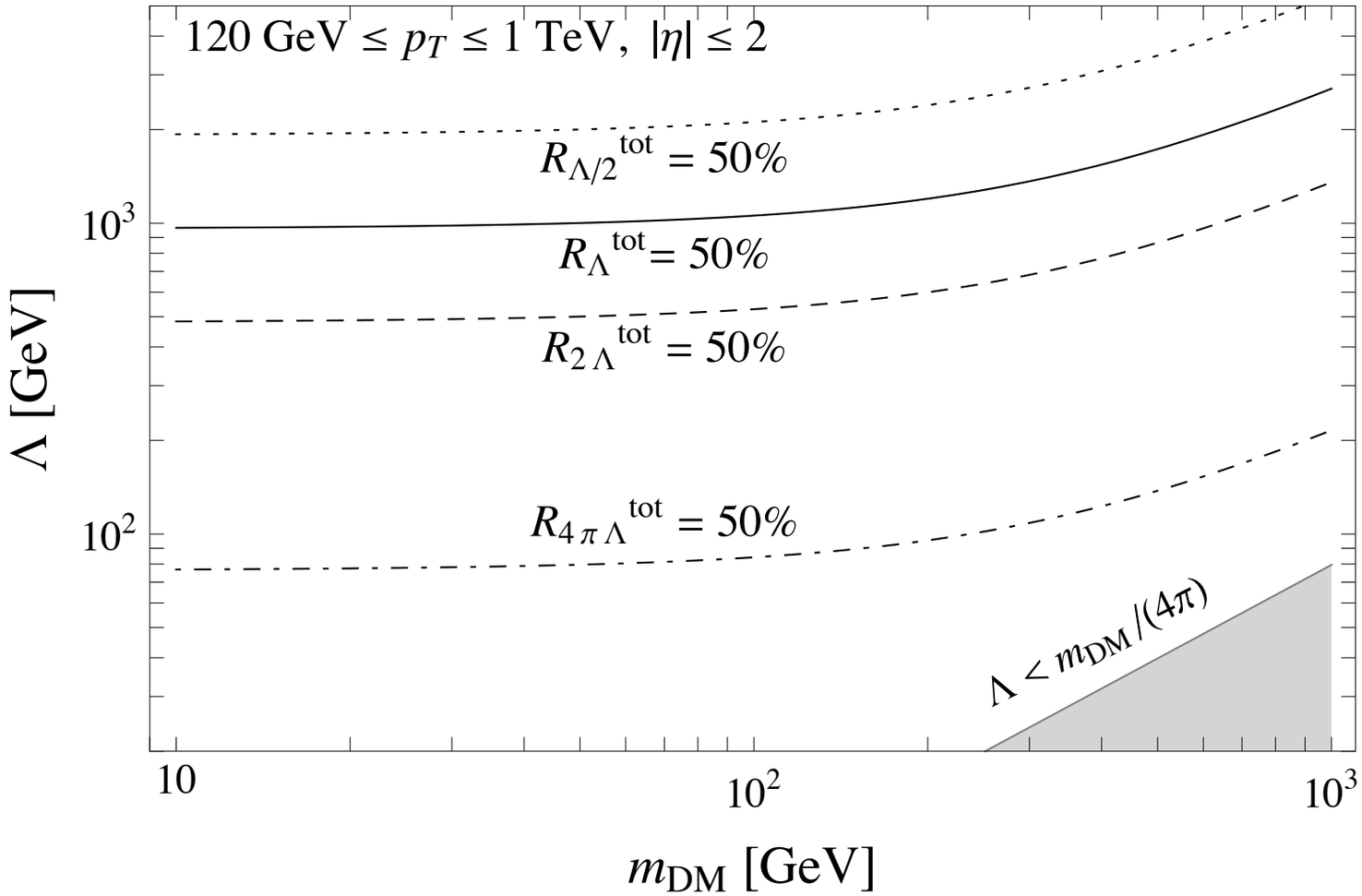




$$\frac{g^2}{M^2} = \frac{1}{\Lambda^2}$$

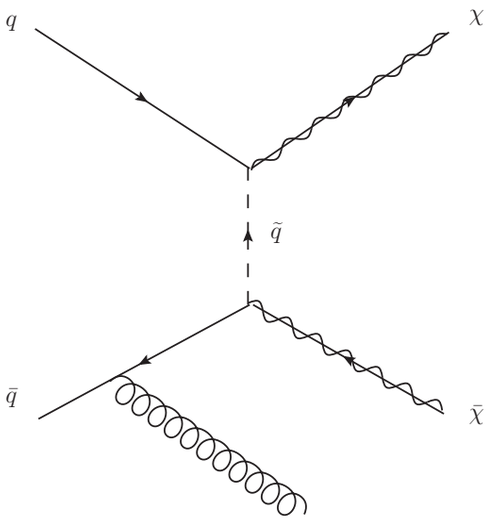
How full is the glass?

How full is the glass?

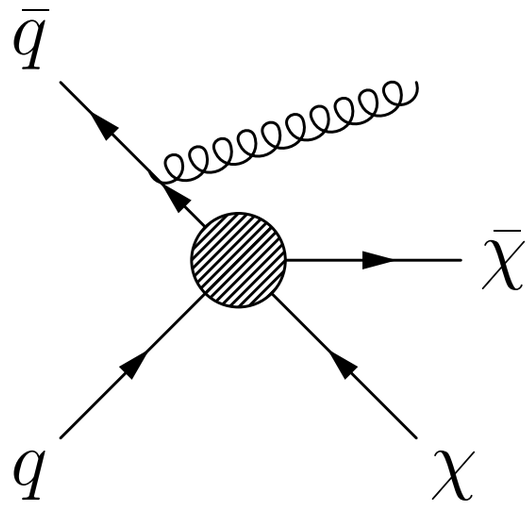
Simplified Models

"Integrate in" the mediator

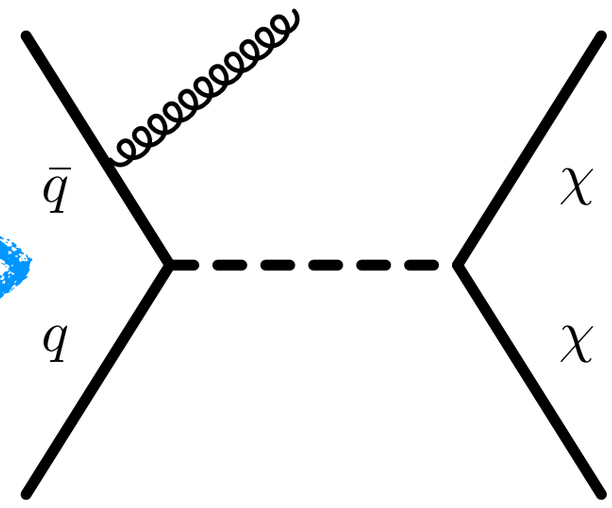
t-channel



EFT



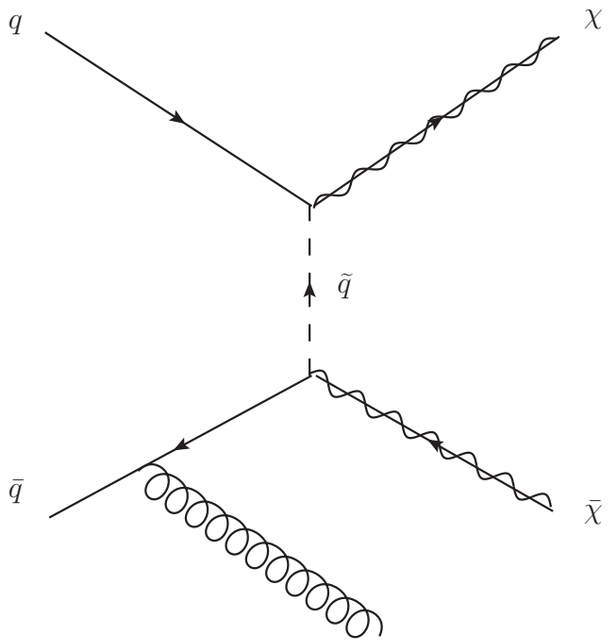
s-channel



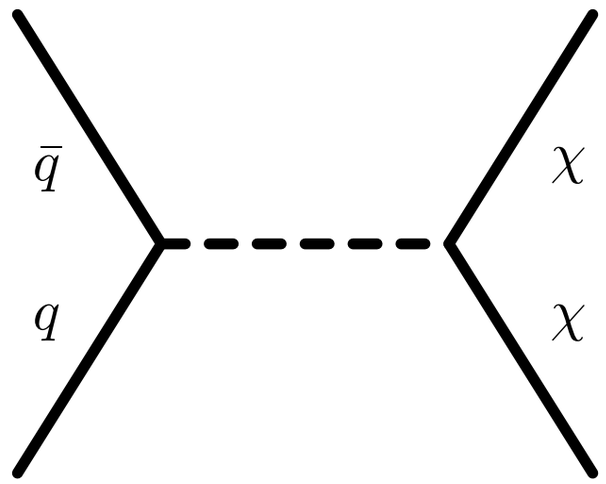
$$\Lambda,\, m_\chi \longrightarrow m_\chi,\, M,\, \Gamma,\, \sqrt{g_q g_\chi}$$

New channels to search for!

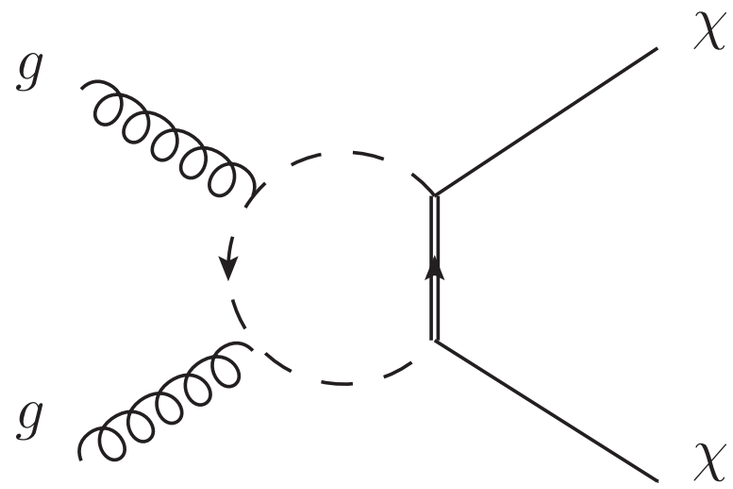
Simplified Models



t-channel



s-channel



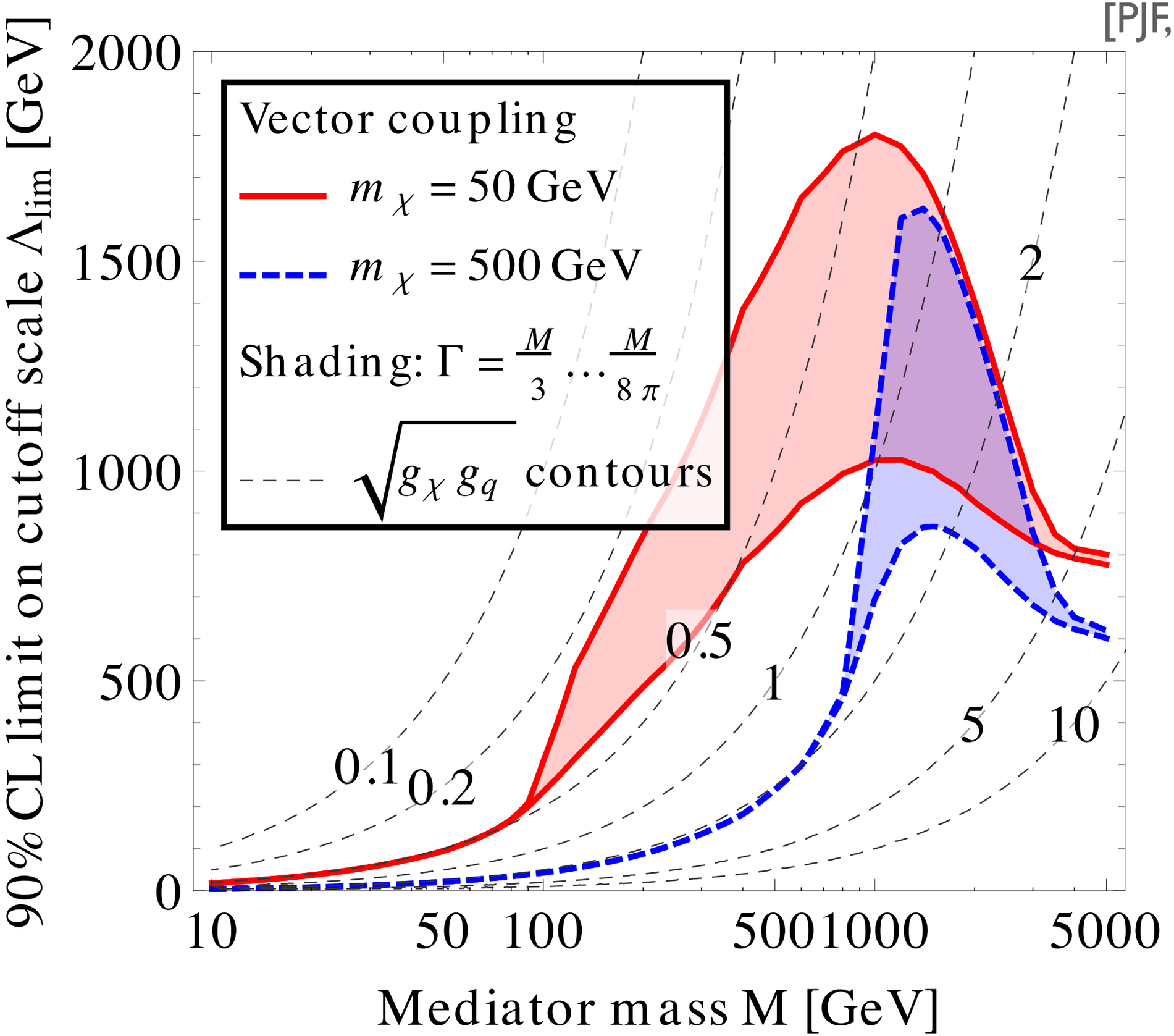
loop

"Full" simplified model alters kinematics, search strategies, brings in new model dependence

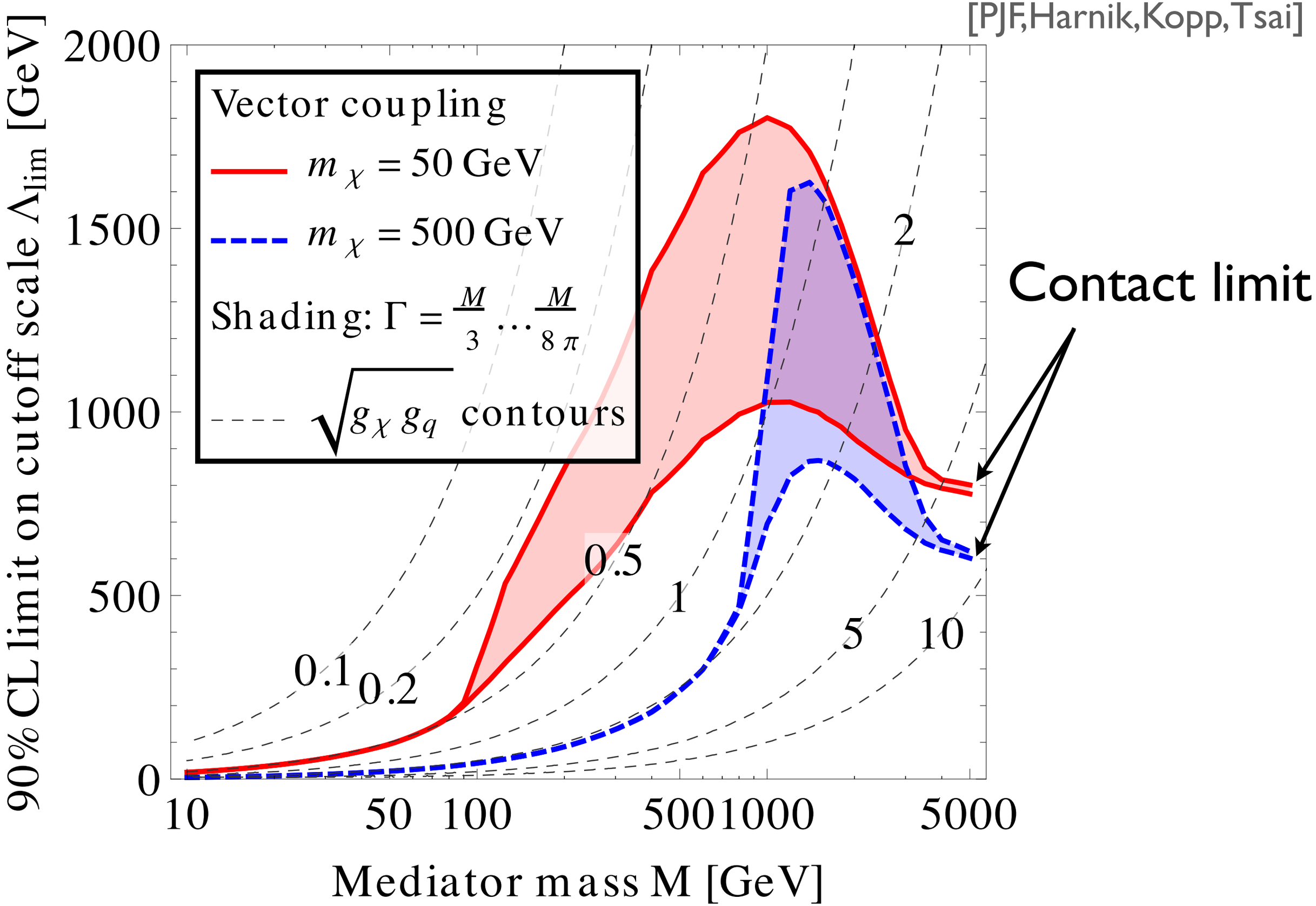
Nothing new, we can deal with this

There are additional states/channels to search for

[PJF,Harnik,Kopp,Tsai]



[PJF,Harnik,Kopp,Tsai]



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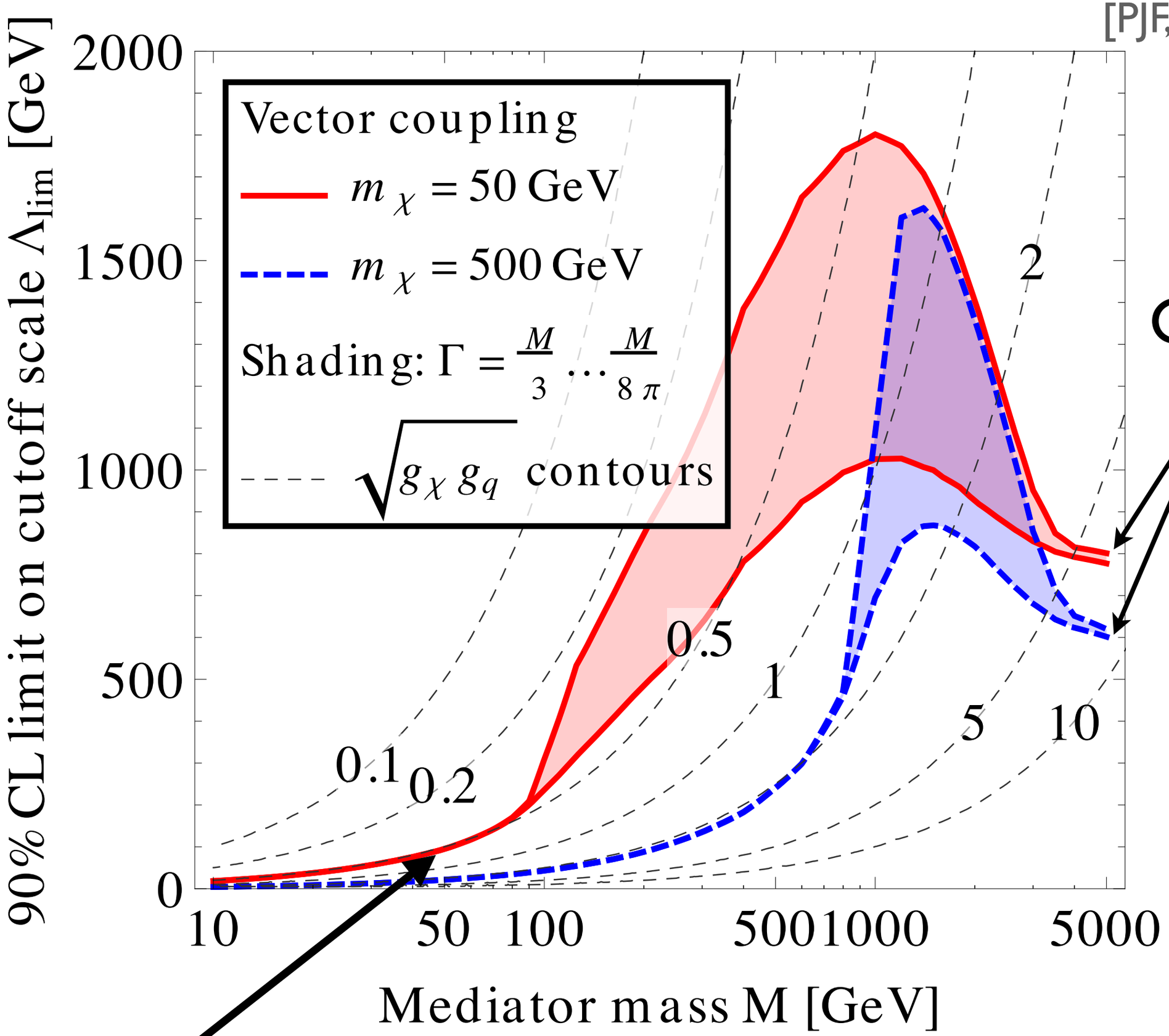
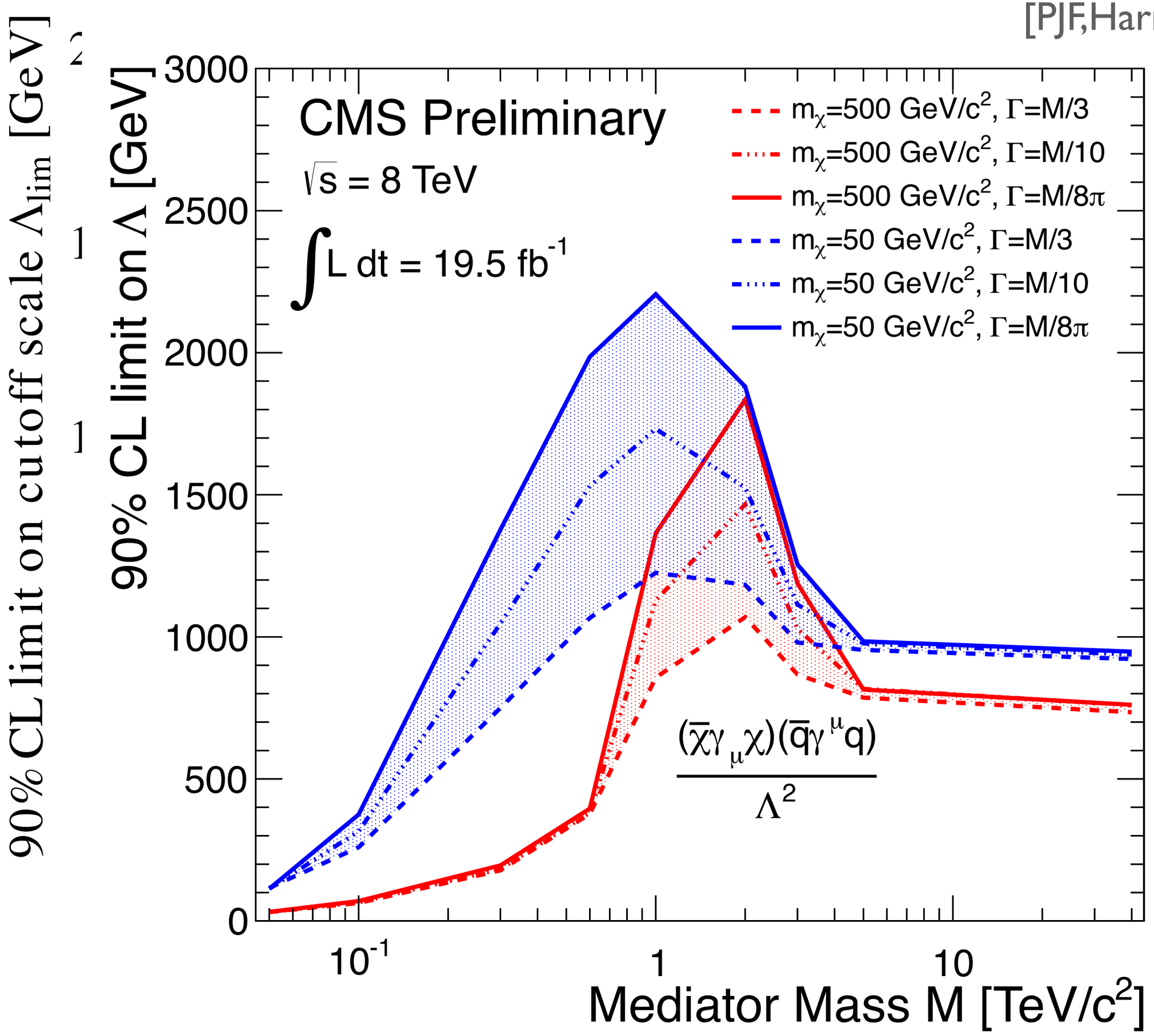


Contact limit

Light mediator severely weakens limit

[PJF,Harnik,Kopp,Tsai]

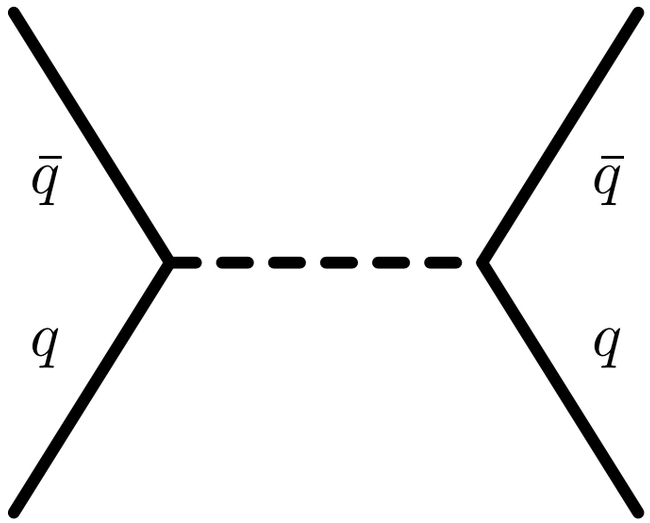


tact limit

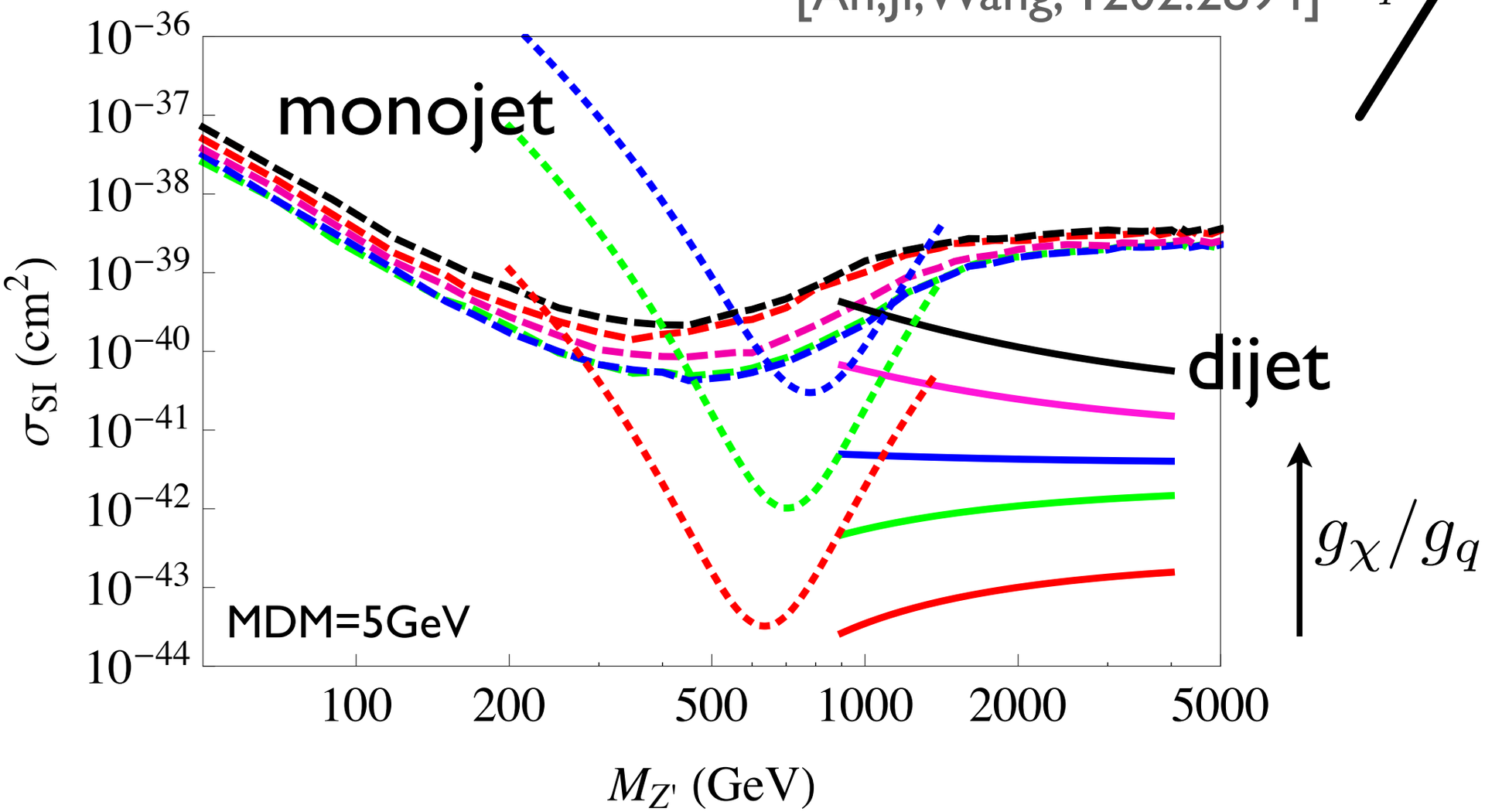
Light Mediators

[An,Ji,Wang:1202.2894;March-Russell, Unwin, West: 1203.4854]

Look for the light mediator directly-dijet resonance/angular distributions



[An,Ji,Wang, 1202.2894]



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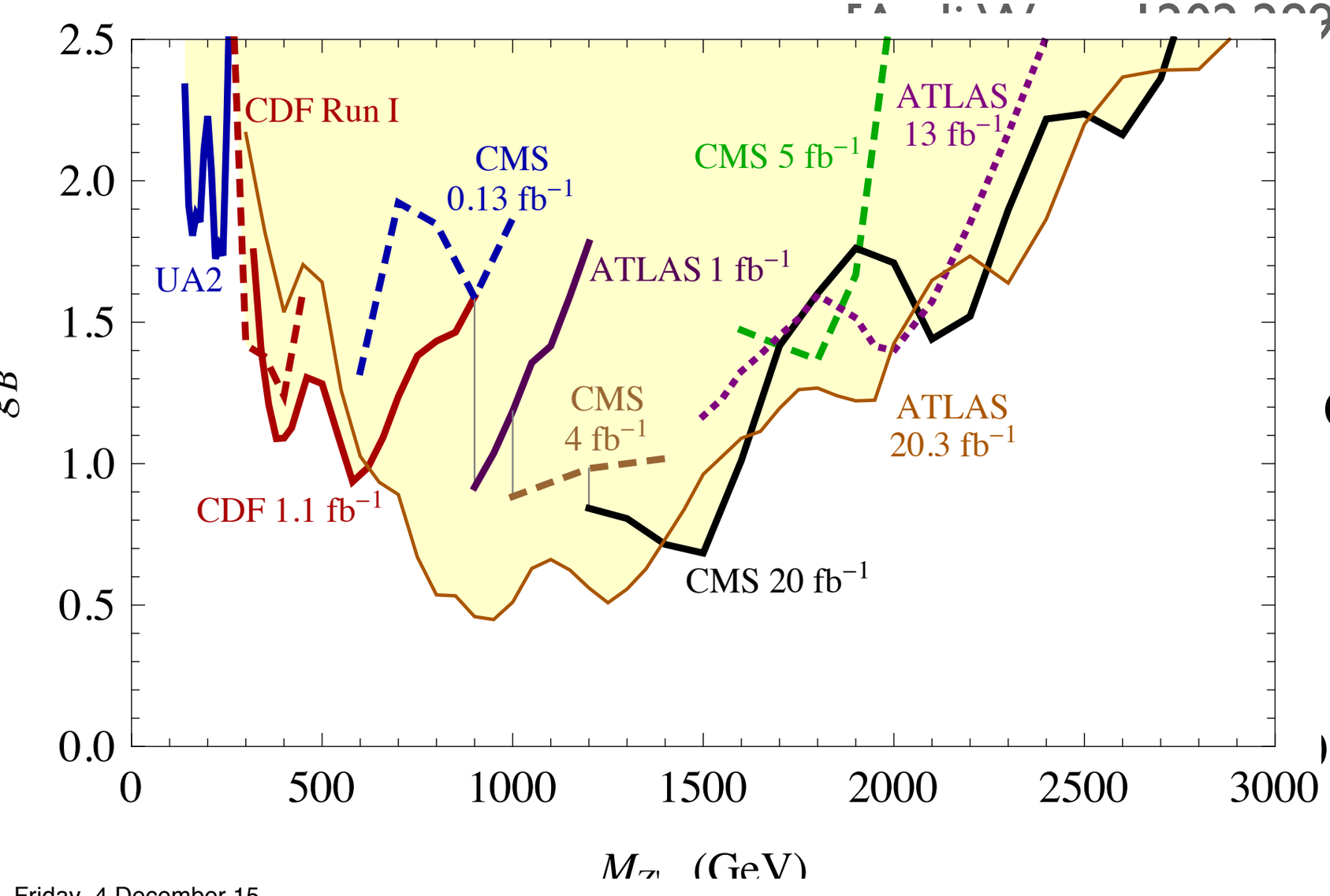

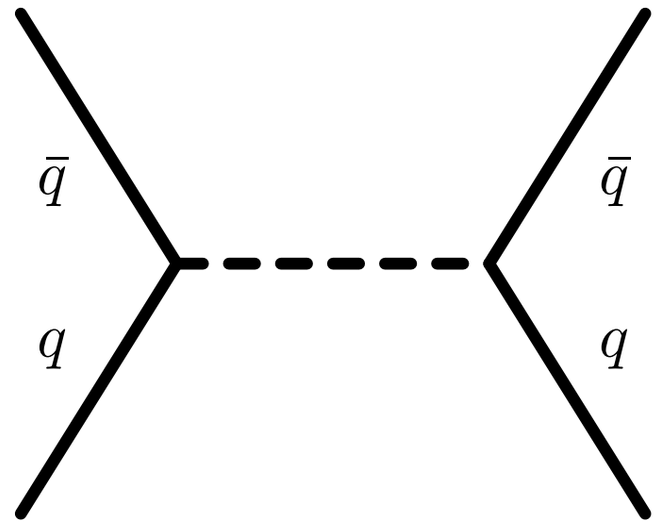

et

g_χ / g_q

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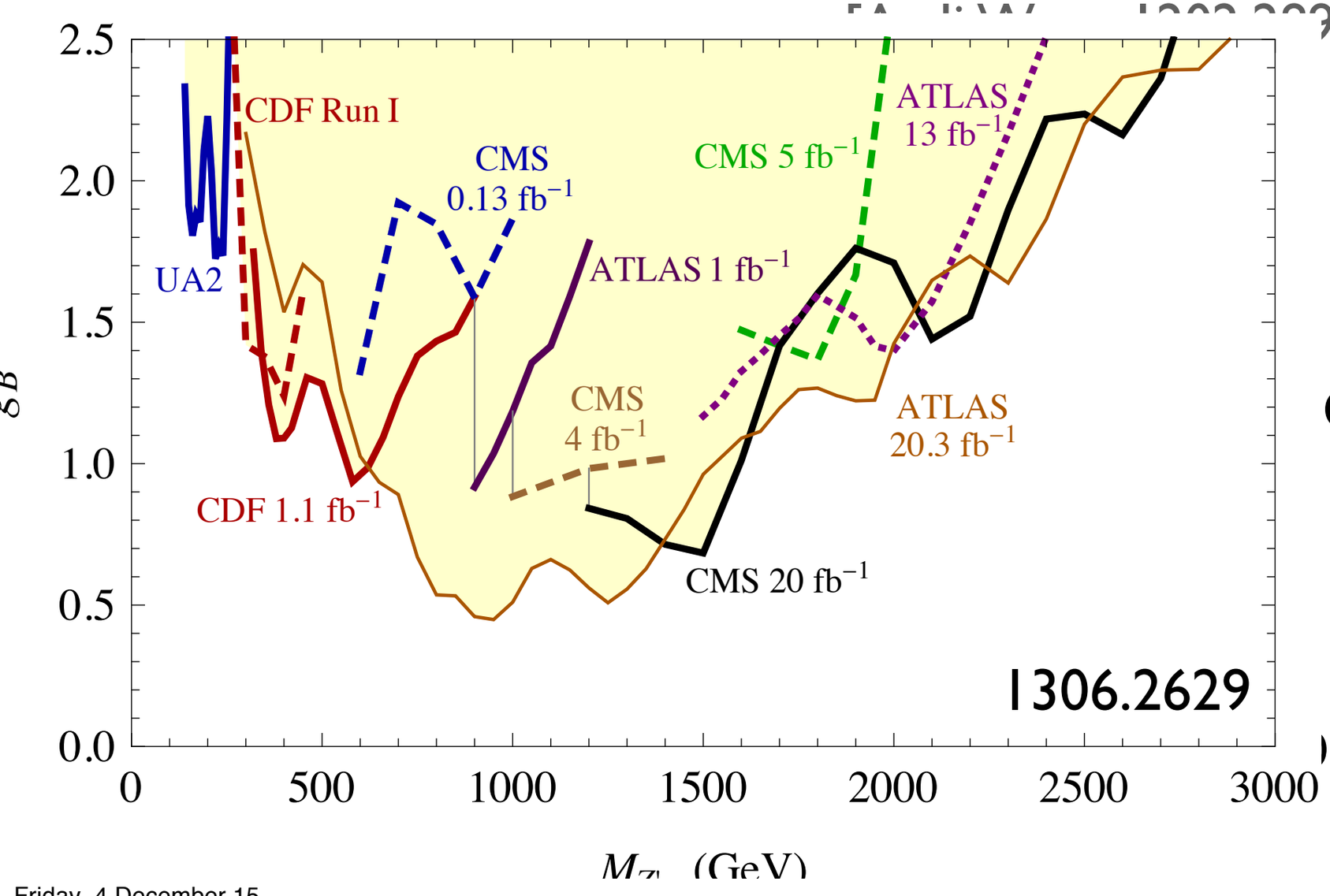
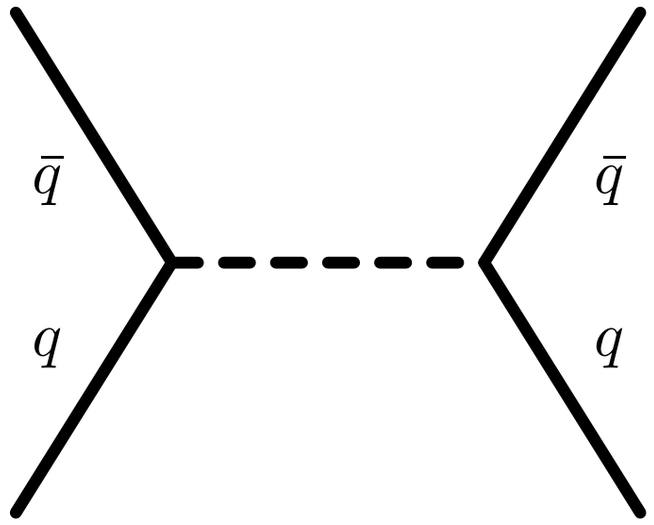




et

g_χ / g_q

Higgs and DM

[Fox, Harnik, Kopp, Tsai]

(See Matthew's talk on Saturday)

- The Higgs exists. DM exists.
- The Higgs is a motivated candidate for mediator of DM interaction. a.k.a. the **Higgs Portal**.
- Assuming Standard Higgs production:

Limit on invisible Higgs.

↓

Limit on Higgs-DM coupling.

↓

Limit on direct detection.

[Fox, Harnik, Kopp, Tsai]

(See Matthew's talk on Saturday)

or mediator of DM

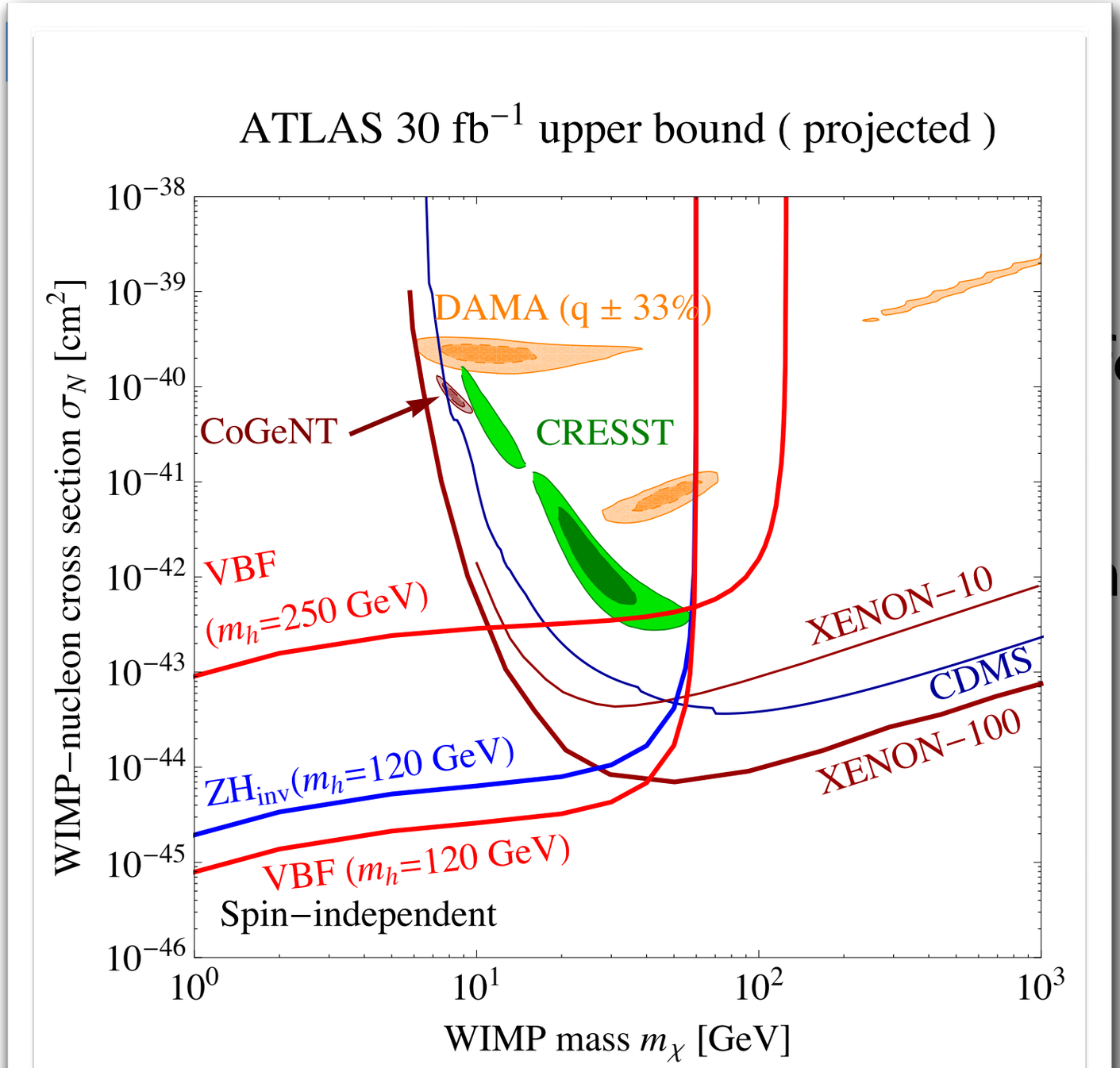
:

Higgs.

Limit on Higgs-DM coupling.

↓

Limit on direct detection.

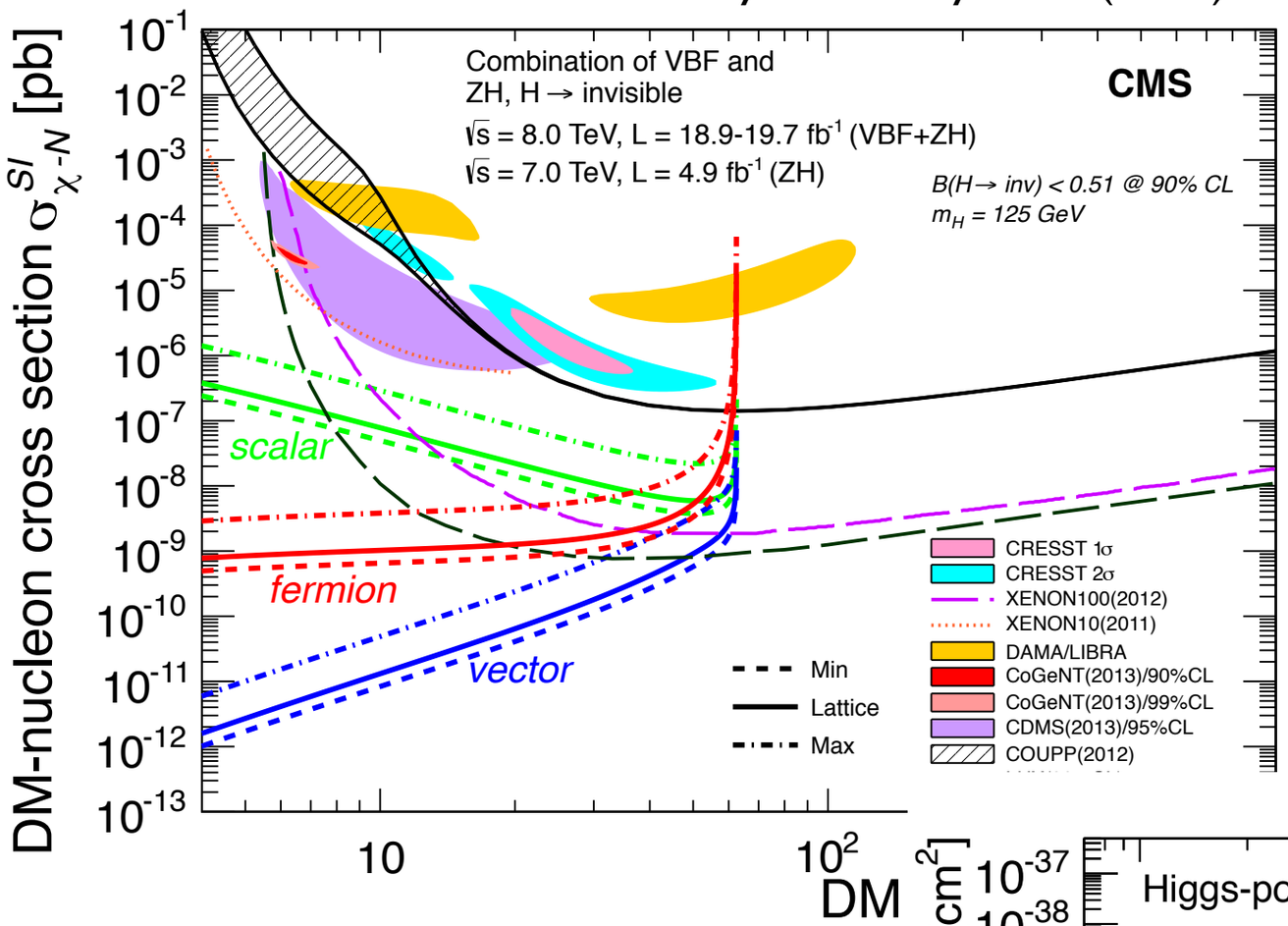


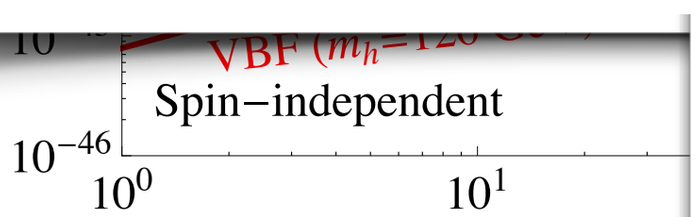
[Fox, Harnik, Kopp, Tsai]

(See Matthew's talk on Saturday)

r mediator of DM

Invisible decay combo by CMS (2014)

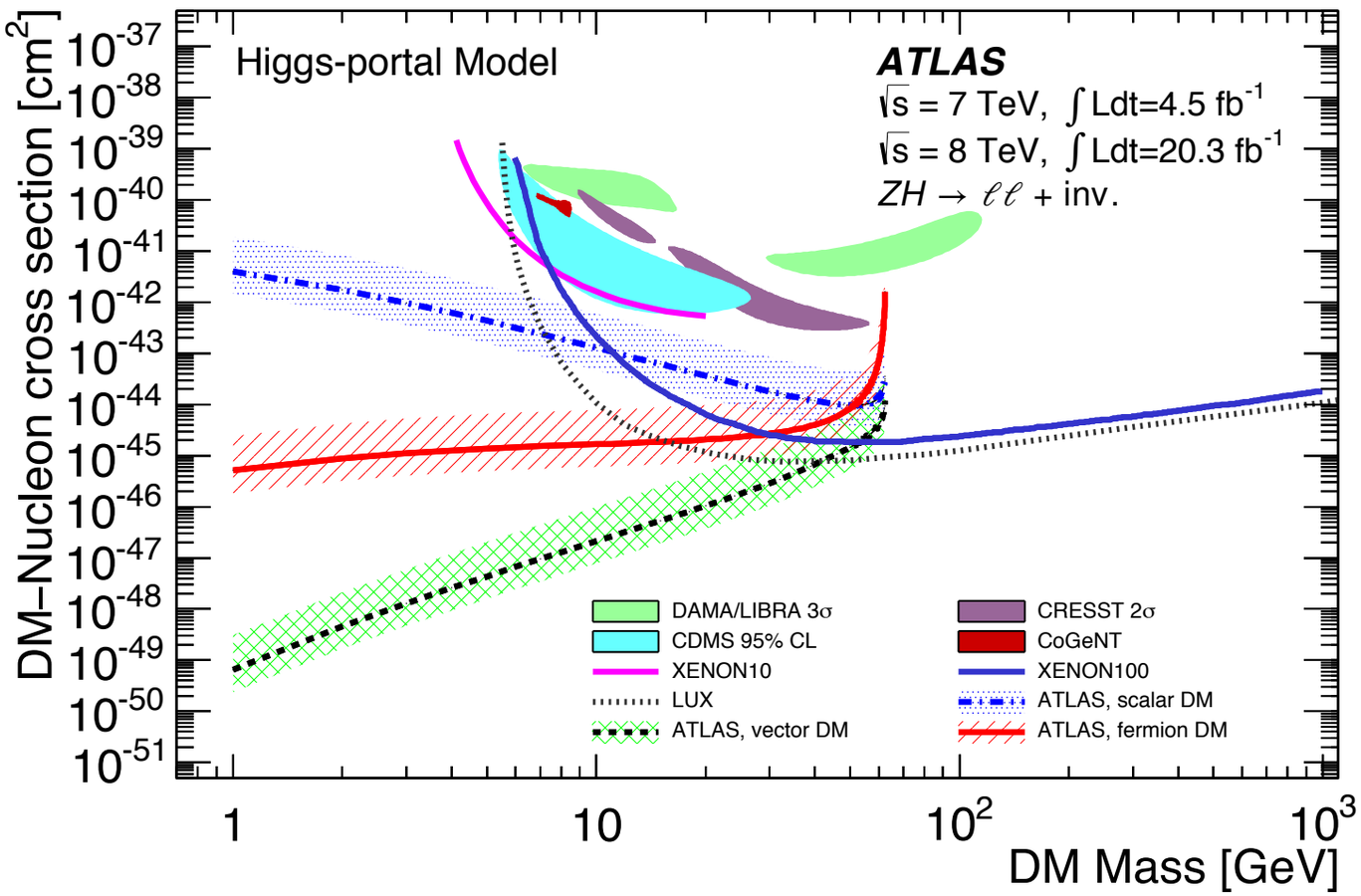




Limi

Lim

PRL on invisible decay by ATLAS (2014)



Where are we going?

Considerable discussion in the community about how to implement DM searches at Run II.

TWiki > LHCDMF Web > WebHome (2015-03-11, AntonioBoveia)

Edit Attach PDF

Welcome to the ATLAS-CMS DM Forum Twiki Web

The ATLAS and CMS experiments have created an informal Dark Matter forum (LHC-DMF) to harmonize the Dark Matter benchmarks used by both experiments for Run 2. The forum will also address the presentation of results, particularly the comparison with non-collider experiments. The full goals of the forum are described in the Mandate.

The aim of this Forum is to actively work with the Dark Matter theory and experimental community, in order to finalize a set of recommendations for both the ATLAS and CMS experiments by February for the LHC Run-2 Dark Matter searches.

EFTs provide an easily digestible encoding of LHC results, should also use a *simple, conservative* truncation. Ultimately we will use a few self-consistent simplified models

Conclusions

- Colliders can place strong constraints on dark matter
- Competitive with direct detection searches
  - Light DM
  - Spin dependent
  - *Independent of all astrophysics uncertainties*
- Must be aware of caveats in results (**as always**)
- Light mediators alter collider bounds, more parameters, more things to search for
- Simplified models provide a good framework
- Beware of model dependence
- Correlated searches (mono-X, jets+MET, dijets,...)

Lots of work to do!