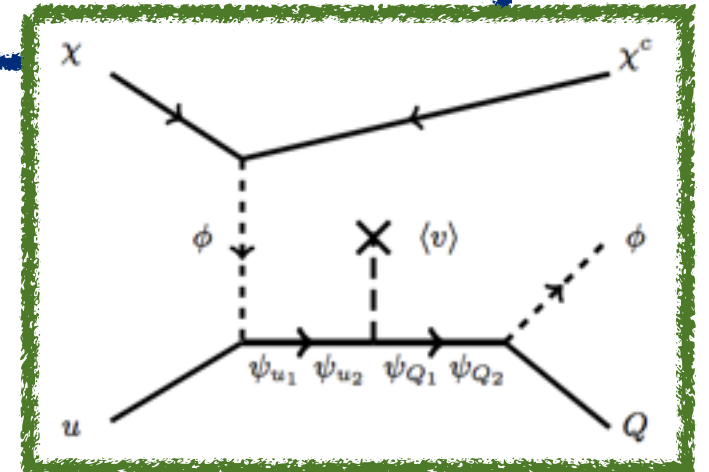


# Direct Detection of the Dark Mediated DM

Yuhsin Tsai

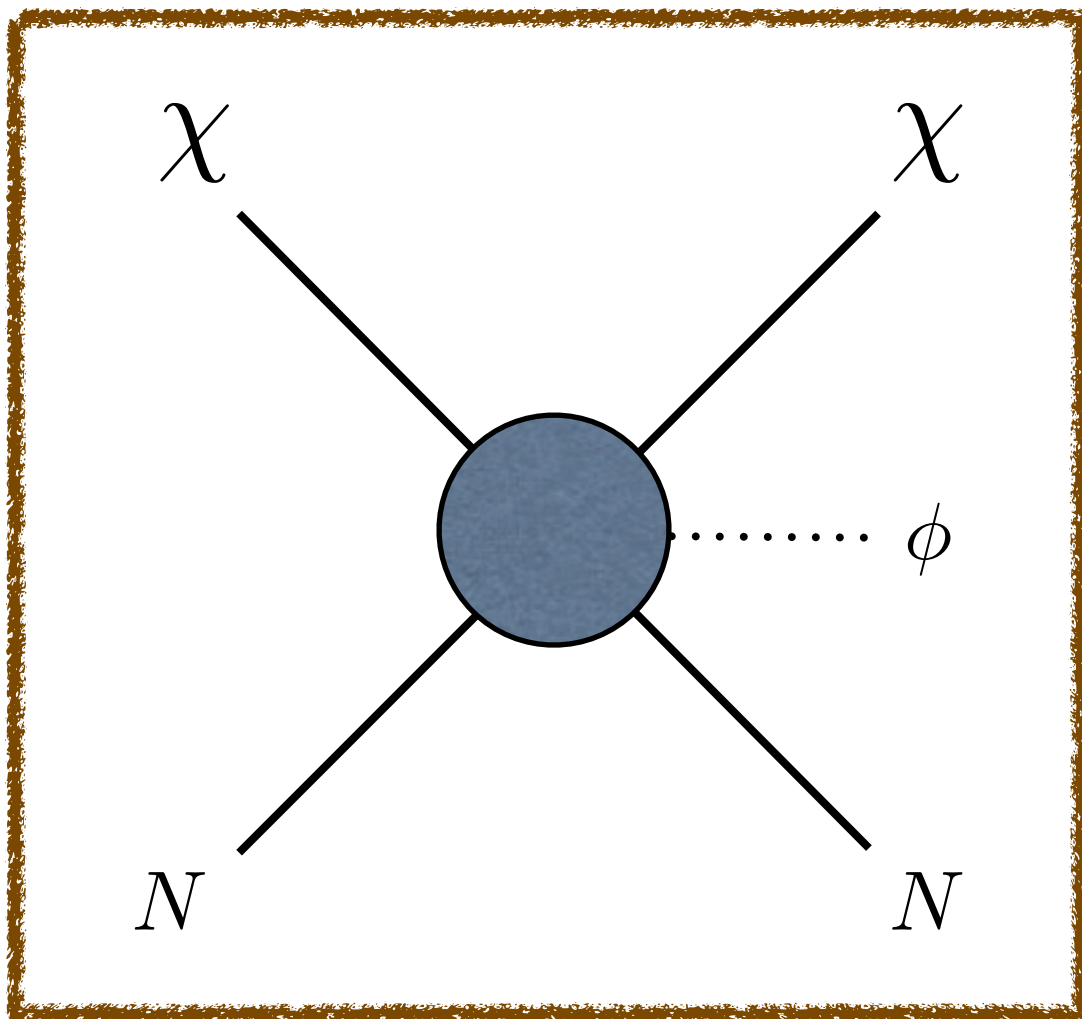


In collaboration with David Curtin, Ze'ev Surujon, and Yue Zhao

1312.2618 and 1402.XXXX

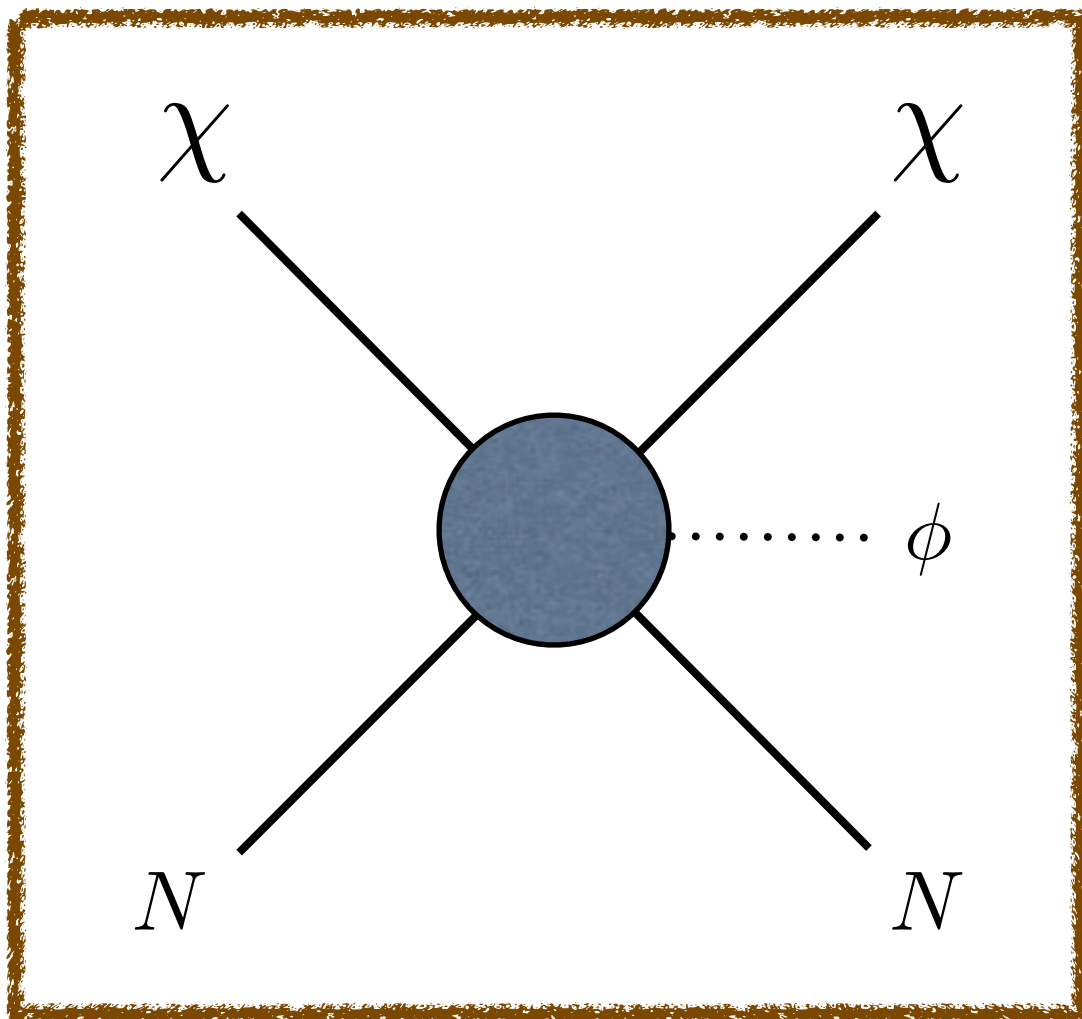
UC Irvine Feb 04 2014

# Main questions



How does the direct detection look like?

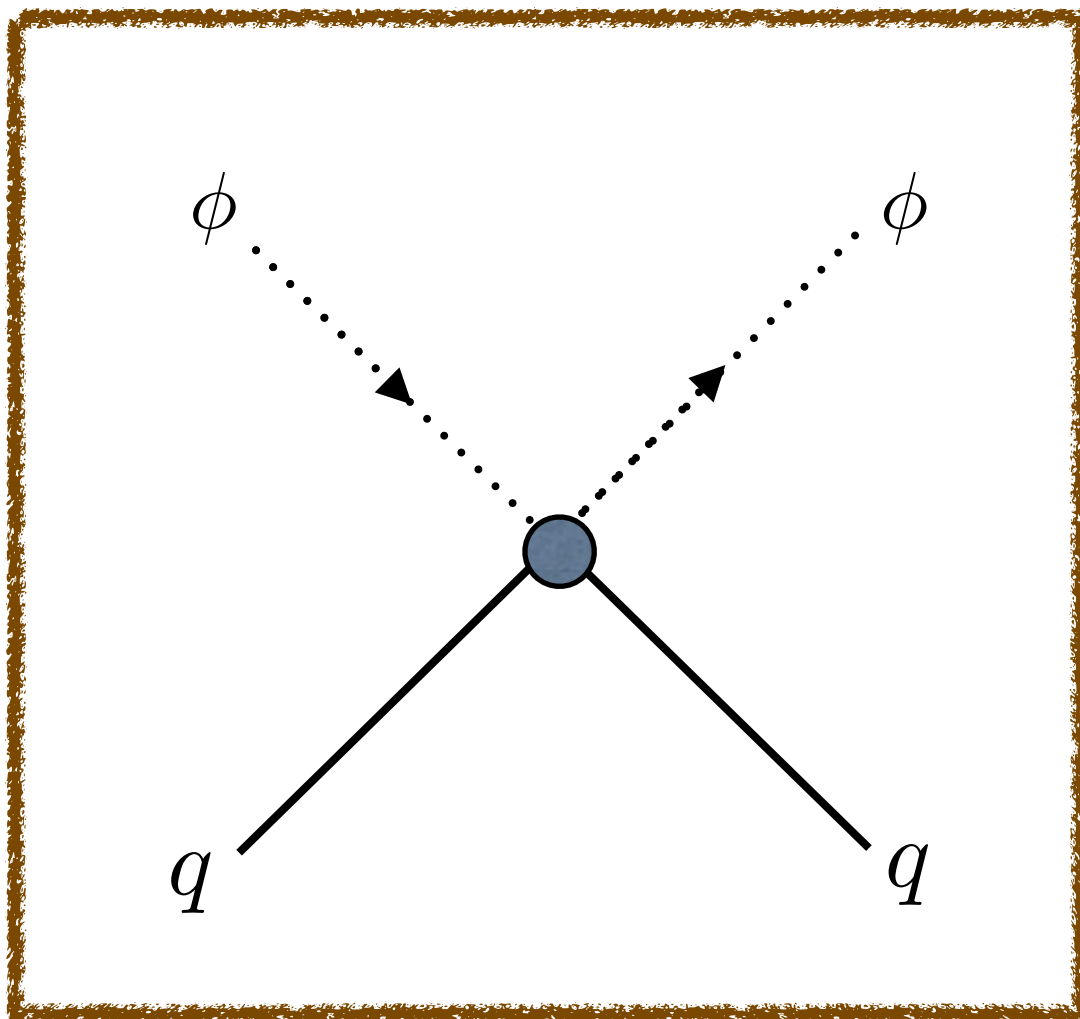
# Main questions



How does the direct detection look like?

What kind of models can give this process?

# Main questions



**dark mediator Dark Matter**

How does the direct detection look like?

What kind of models can give this process?

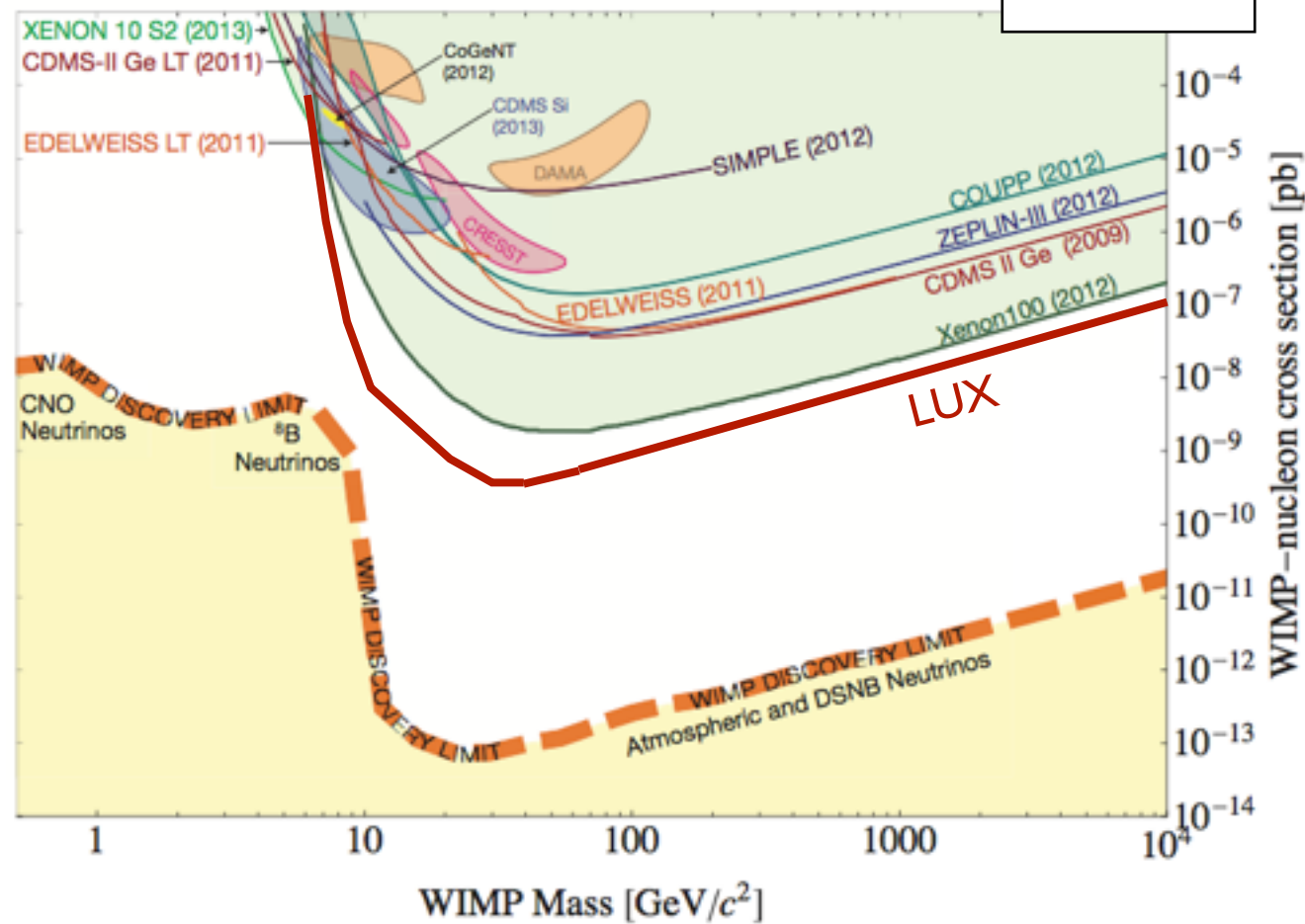
What is the bound on this light scalar – quark coupling?



# Current DM experiments

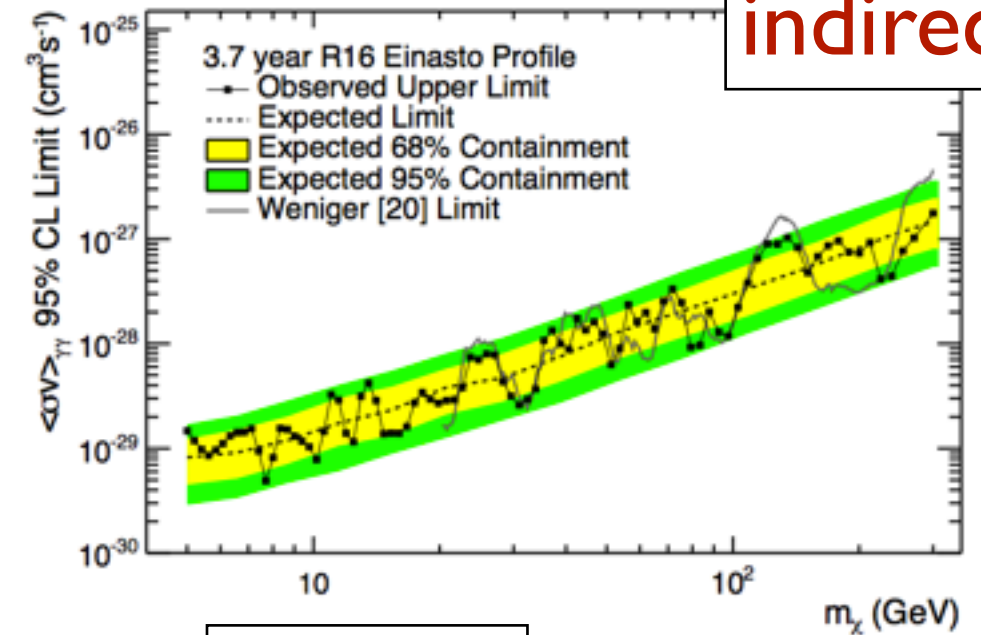
J. Billard and E. Figueroa-Feliciano (13)

direct

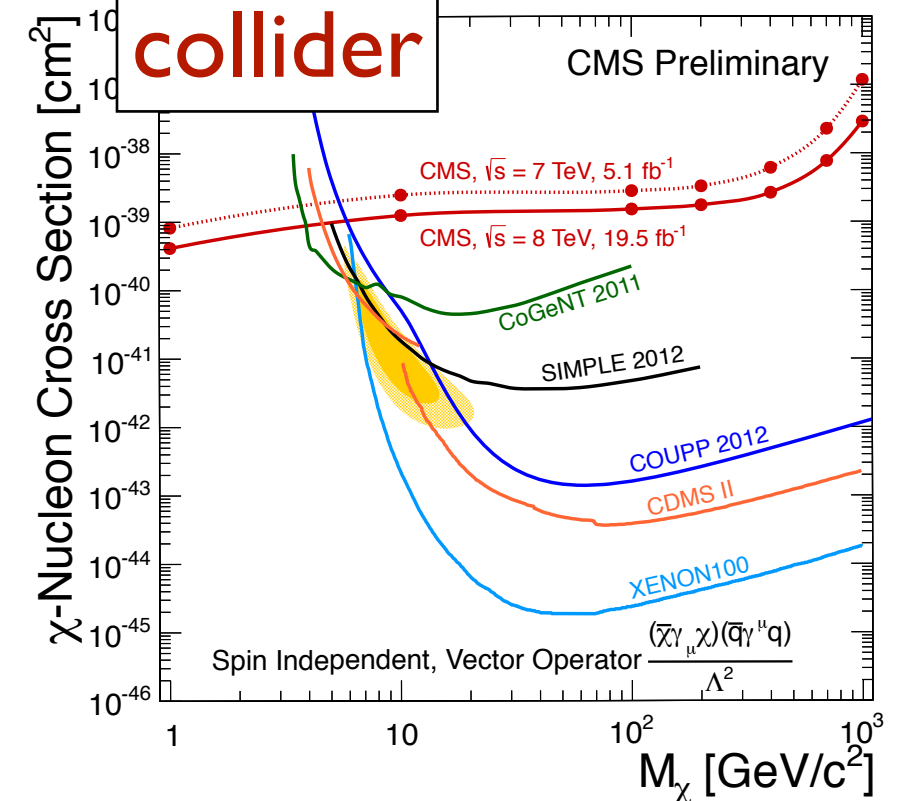


FERMI

indirect



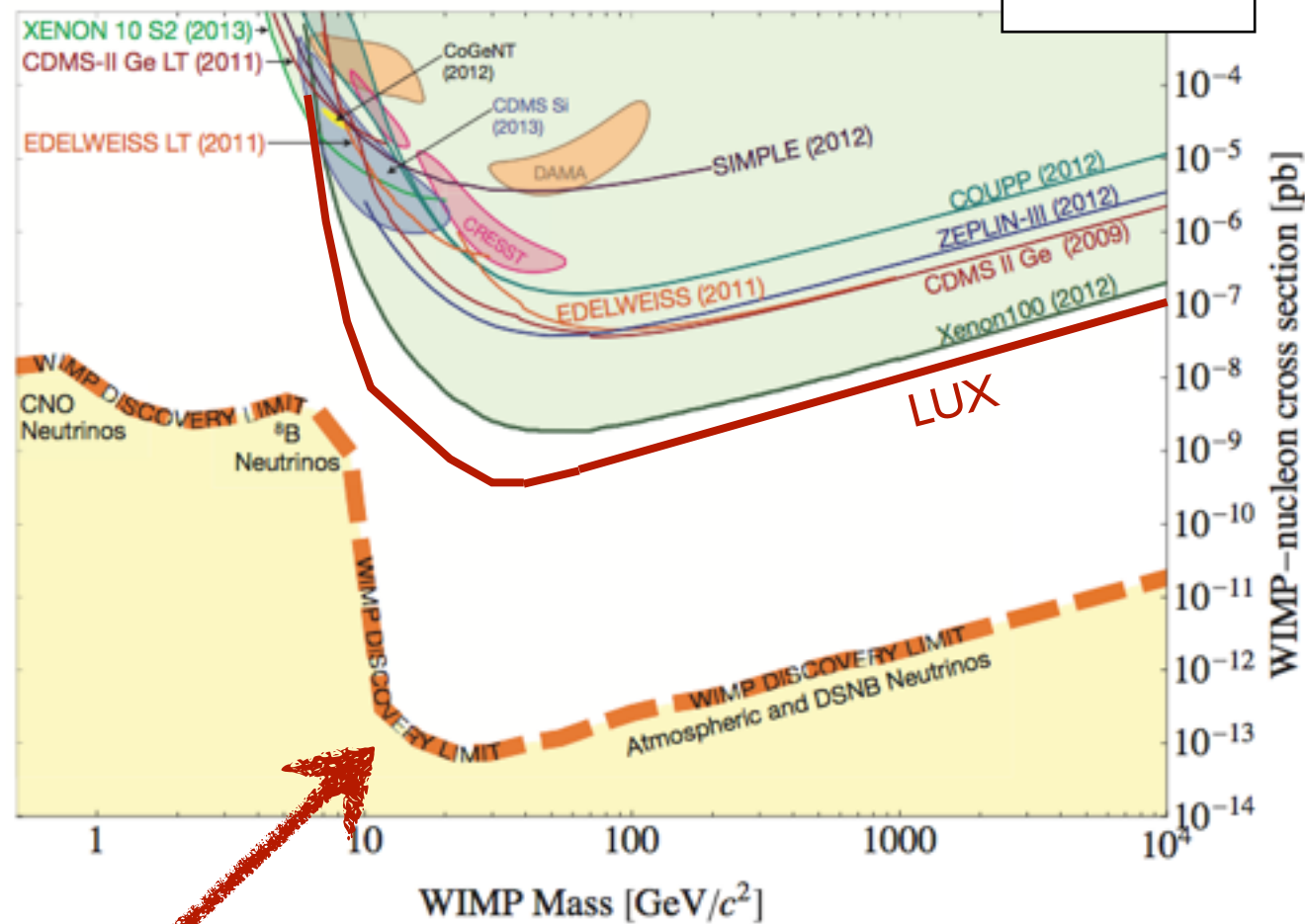
collider



# Current DM experiments

J. Billard and E. Figueroa-Feliciano (13)

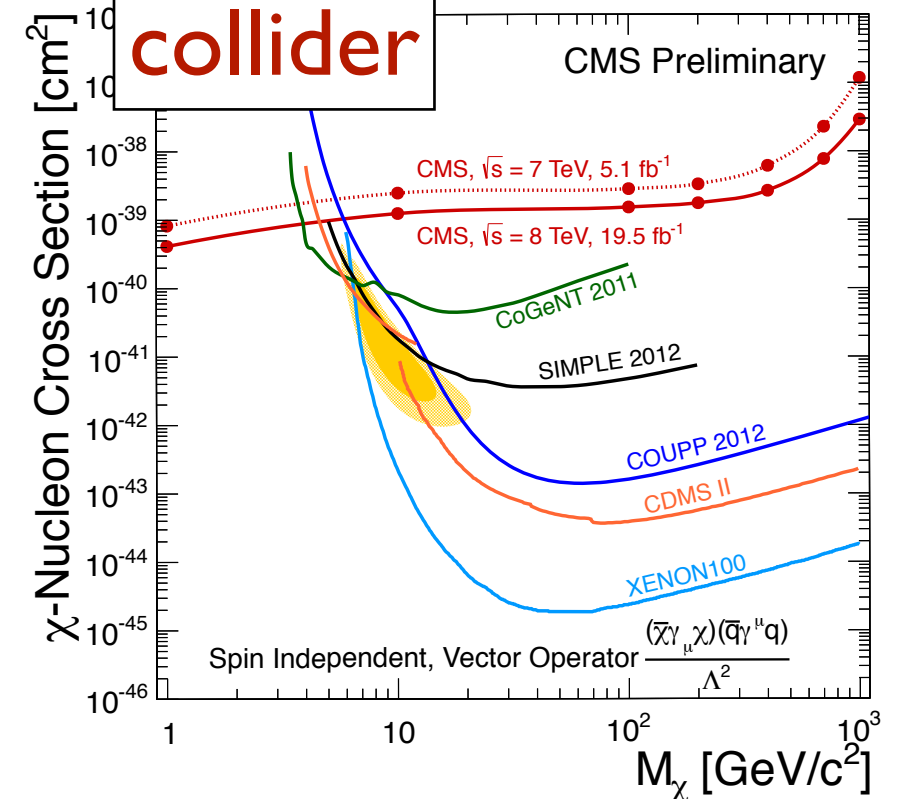
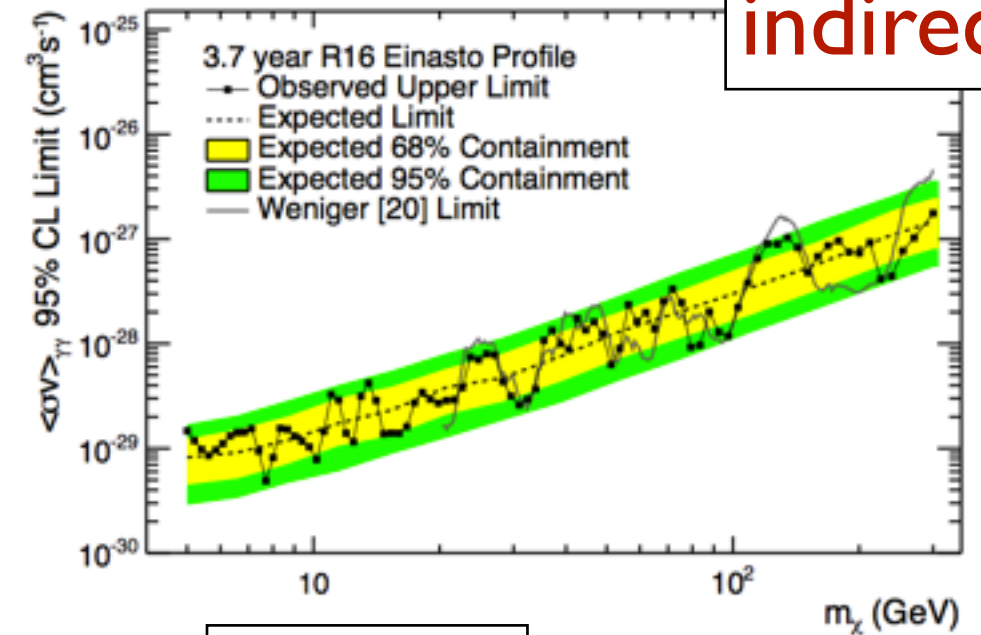
direct



irreducible neutrino-background  
sets a lower bound on the discovery

FERMI

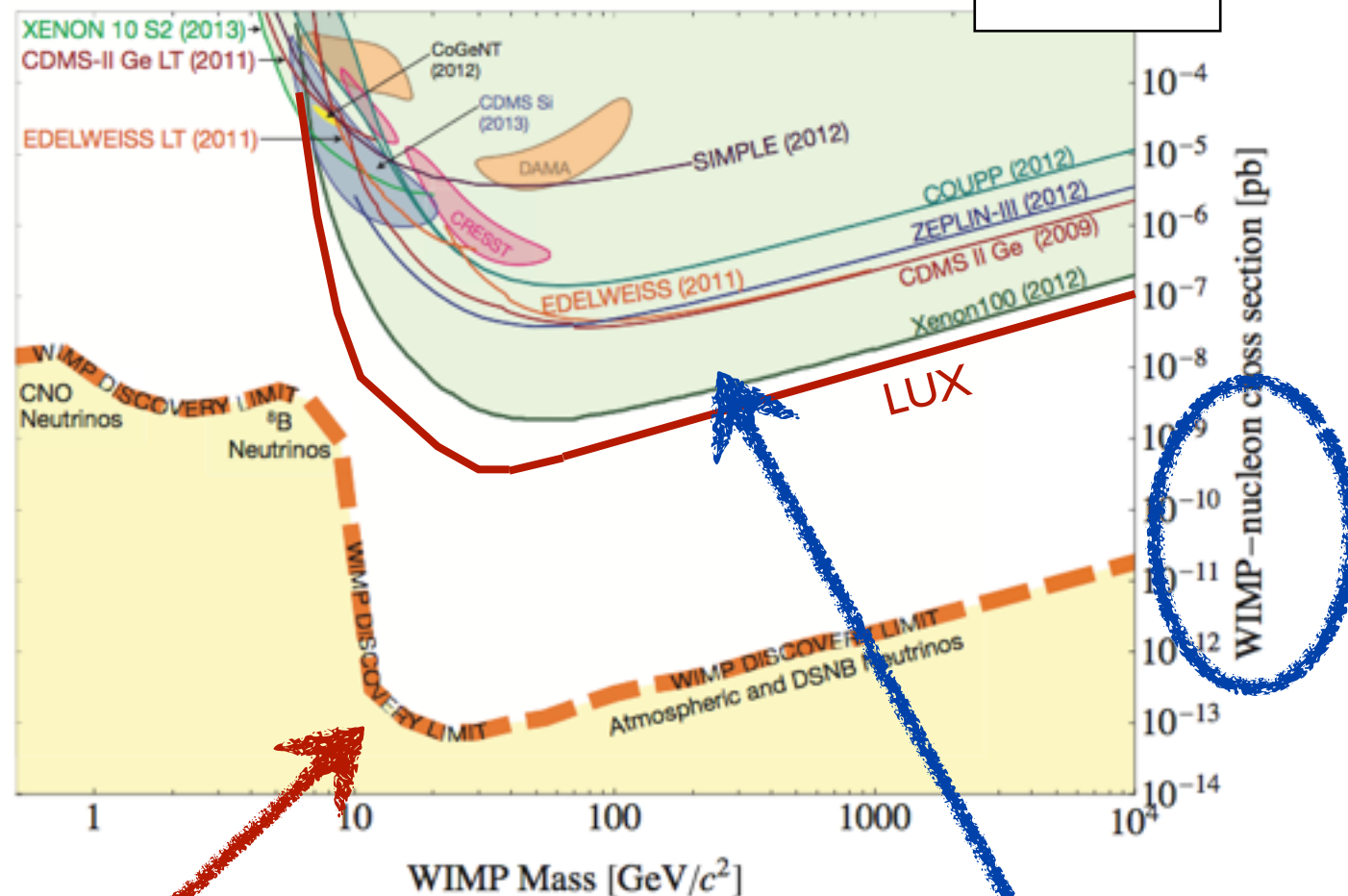
indirect



# Current DM experiments

J. Billard and E. Figueroa-Feliciano (13)

direct

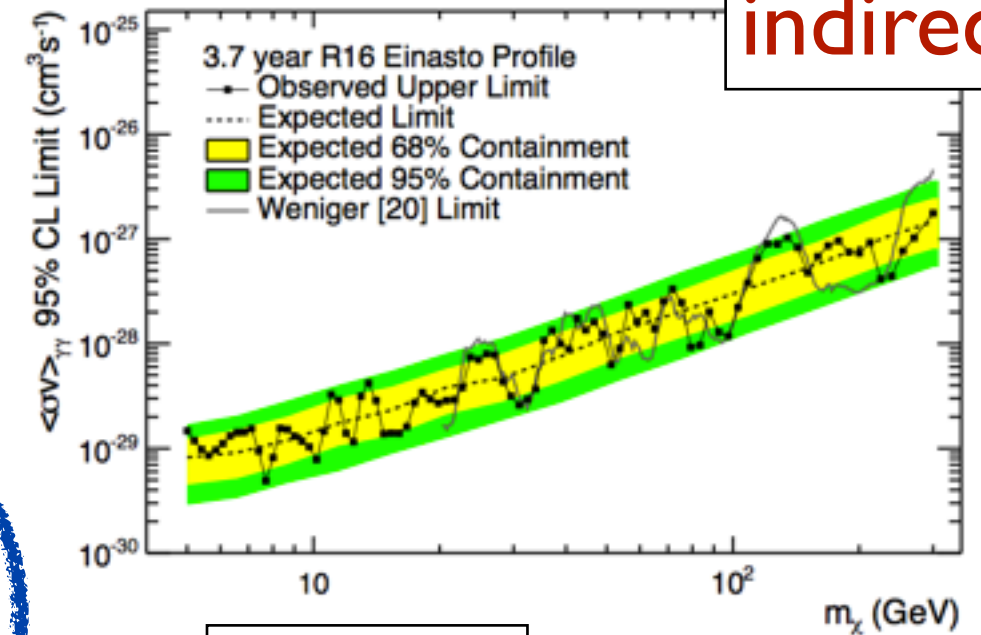


irreducible neutrino-background sets a lower bound on the discovery

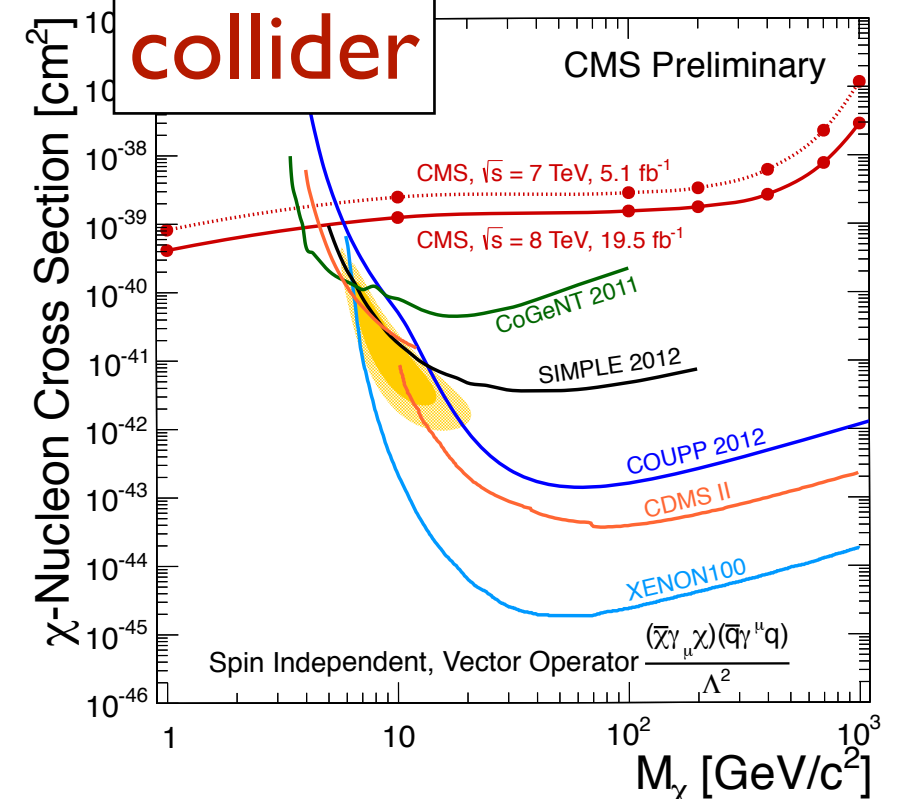
assume 2 to 2 scatterings with a contact DM-quark coupling

FERMI

indirect

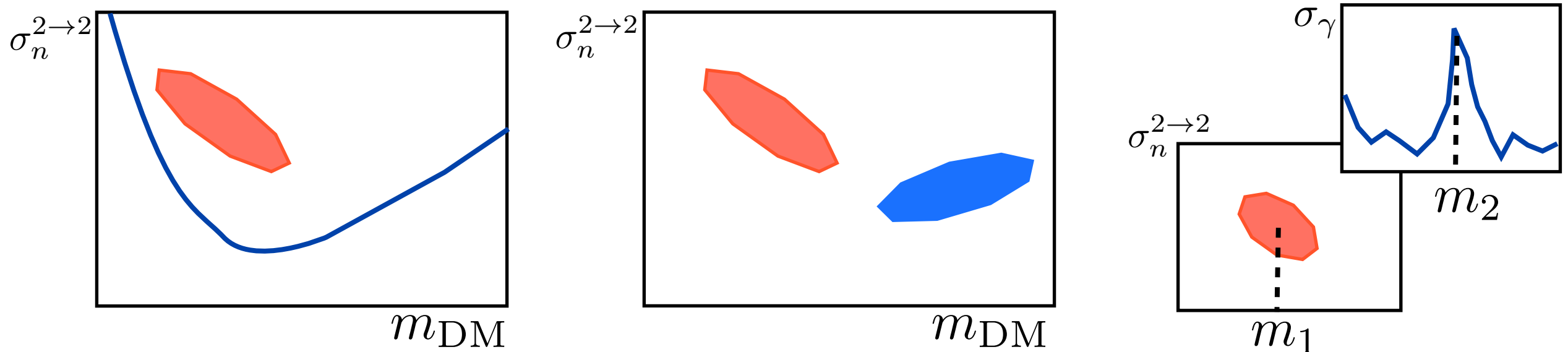


collider



# Useful inconsistencies

The inconsistencies between different experiments may reflect the detailed structure of the dark sector

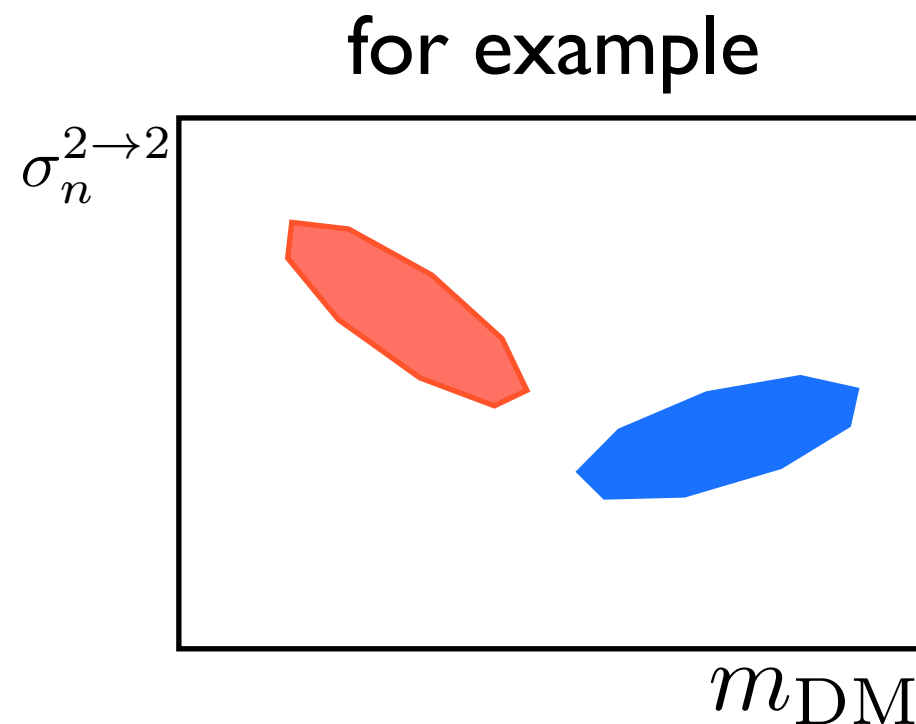
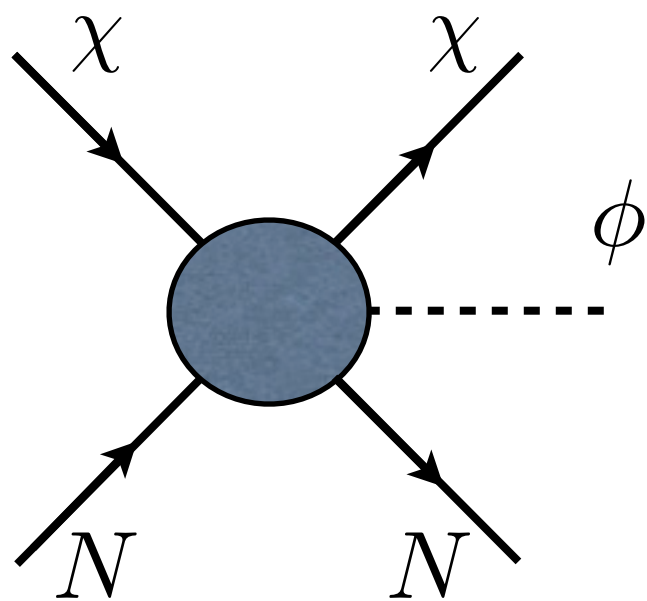


Existing ideas: exothermic DM, isospin violation, non-standard form factors, multi-component DM, ... **all assume 2to2 scattering so far**

It is important to explore a more complete set of DM models to explain the future data

# Missing ingredient: different topology

The exotic scattering process can provide new tools in understanding different experimental results

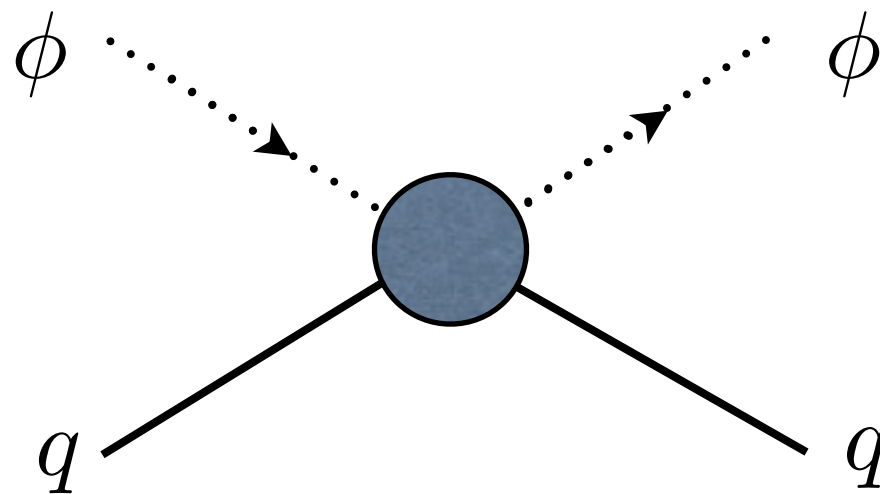


- the recoil spectrum has a non-trivial  $m_N$  dependence
- get different DM masses when assuming a WIMP-like process



# A model building motivation

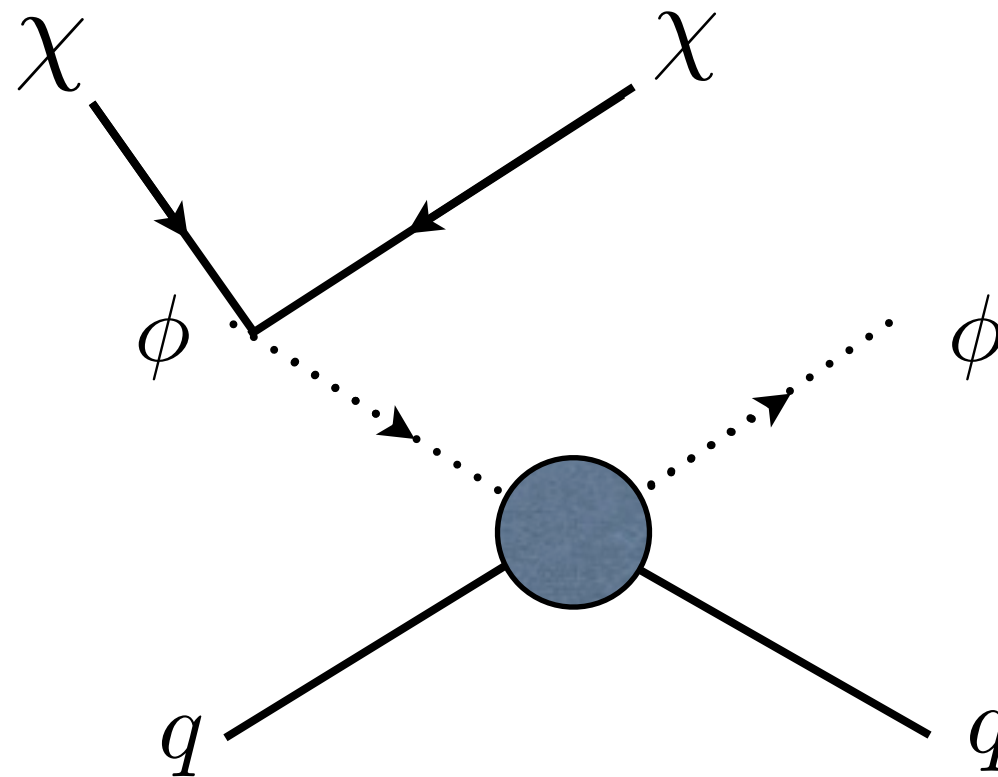
It is natural to have a “**dark**” mediator in the dark sector



**dark** **m**ediator **D**ark **M**atter

# A model building motivation

It is natural to have a “**dark**” mediator in the dark sector

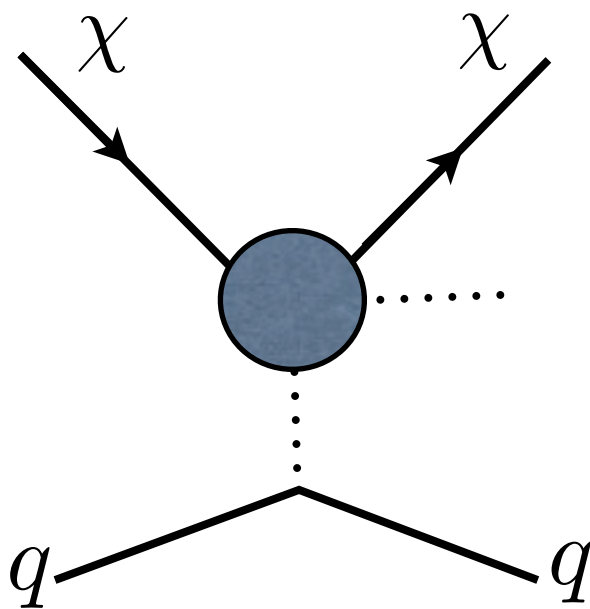


**dark mediator Dark Matter**

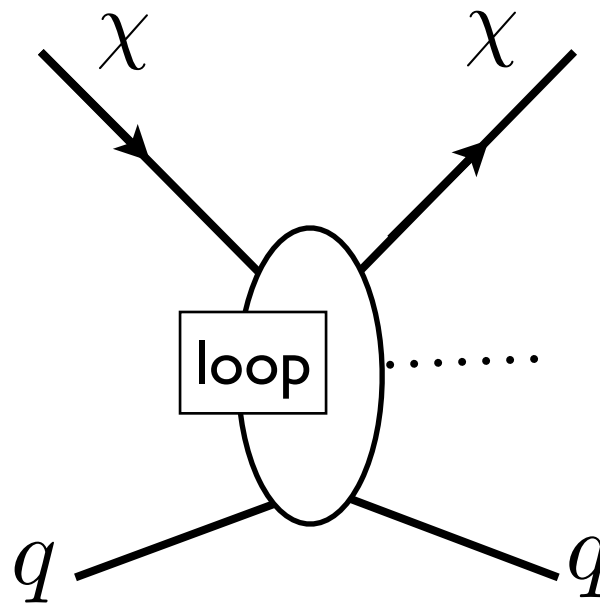
A natural way to have the 2 to 3 scattering

# Other ways of getting 2to3 ?

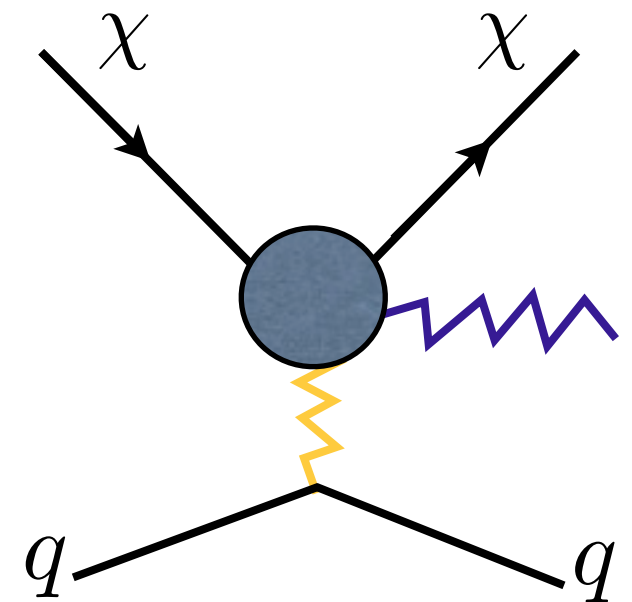
Not easy...



strong bounds on light singlet scalars. hard to avoid the 2 to 2 scattering



the loop suppression makes it hard to have a large cross section

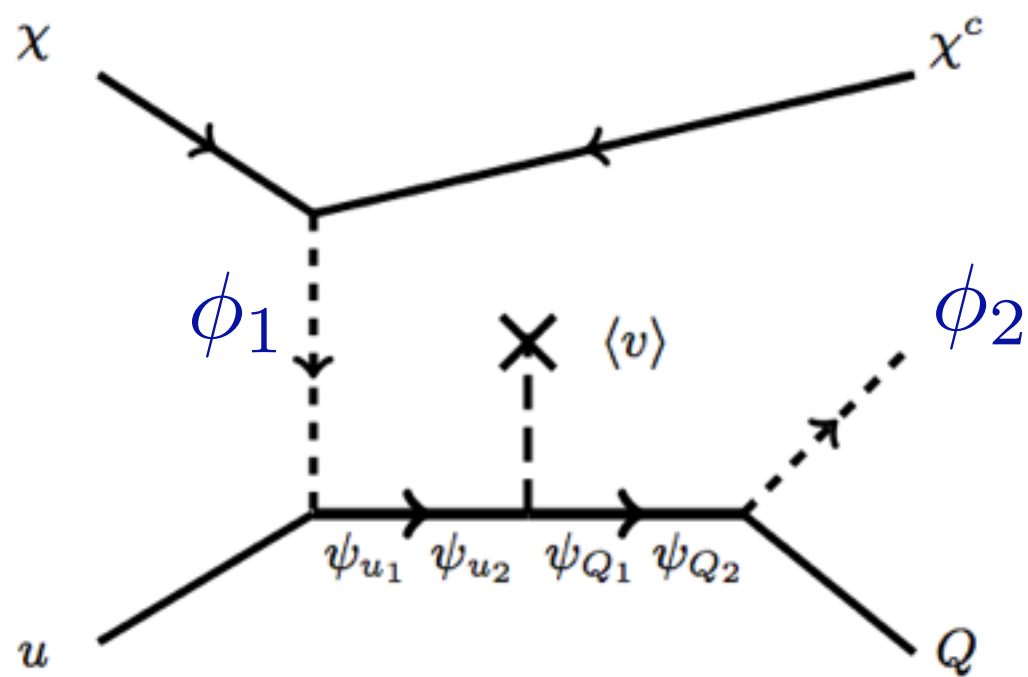


derivative couplings give velocity suppressions, assume DM doesn't carry SM charges

**Focus on the dmDM model in this talk**



# dmDM model with vectorized quarks



	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$Z_3$
$\bar{Q}$	$\bar{3}$	$\bar{2}$	$-1/6$	0
$u$	3	1	$2/3$	0
$d$	3	1	$-1/3$	0
$H$	1	2	$1/2$	0
$\phi$	1	1	0	$2\pi/3$
$\psi_{Q_{1,2}}$	3	2	$1/6$	$2\pi/3$
$\psi_{u_{1,2}}$	3	1	$2/3$	$2\pi/3$
$\psi_{d_{1,2}}$	3	1	$-1/3$	$2\pi/3$
$\chi$	1	1	0	$2\pi/3$

$$\supset \frac{|\phi|^2 \bar{Q} q}{\Lambda} + y_\chi \chi \chi \phi + h.c. \quad \Lambda = \frac{M_Q^2}{y_Q y_q y_{Qq} v}$$

- assume  $\phi_1 = \phi_2 = \phi$ ,  $y_Q = y_q = y_{Qq} = 1$  in the mass basis for simplicity
- there is a  $\sim 0.1\%$  tuning on the light quark yukawa from the  $\phi$  loop
- assume the effective scalar-quark coupling is flavor universal in the mass basis

# Pseudo Light Dark Matter at direct detections



# Direct detection in MadGraph



Si-detector, easy to get, everyone can reproduce the result...

To obtain the recoil spectrum

- generate the DM-quark scattering using **MG5**
- multiply the cross section with the **nuclear form factor**
- convolute the result with **velocity distribution** and **Helm Form Factor**

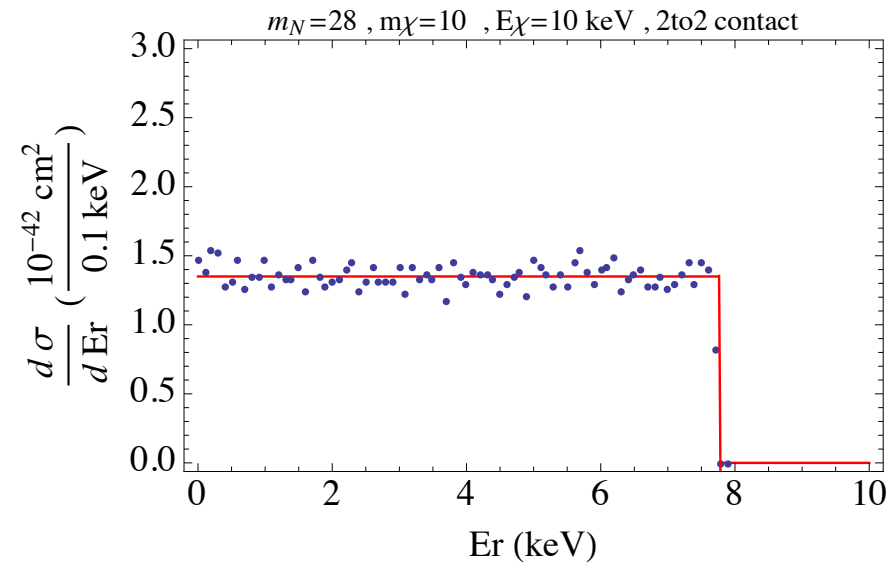
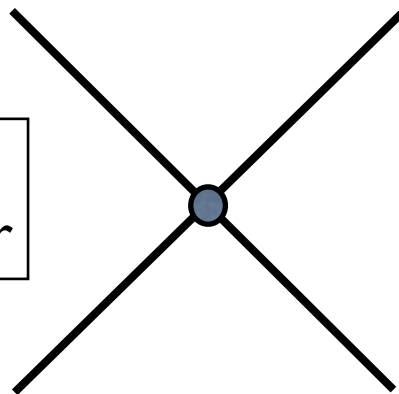
for 2 to 2 contact operator

$$\frac{dR}{dE_r} = N_T \frac{\rho_\chi}{m_\chi} \int dv \, v f(v) \frac{d\sigma_N}{dE_r} \longrightarrow \frac{dR}{dE_r} = \frac{1}{2} \frac{\sigma_n^{\text{SI}}}{\mu_{n\chi}^2} N_T \rho_\chi \frac{m_N}{m_\chi} A^2 F^2(E_r) \int_{v_{\min}(E_r)}^{v_{\max}} dv \, \frac{1}{v} f(v)$$

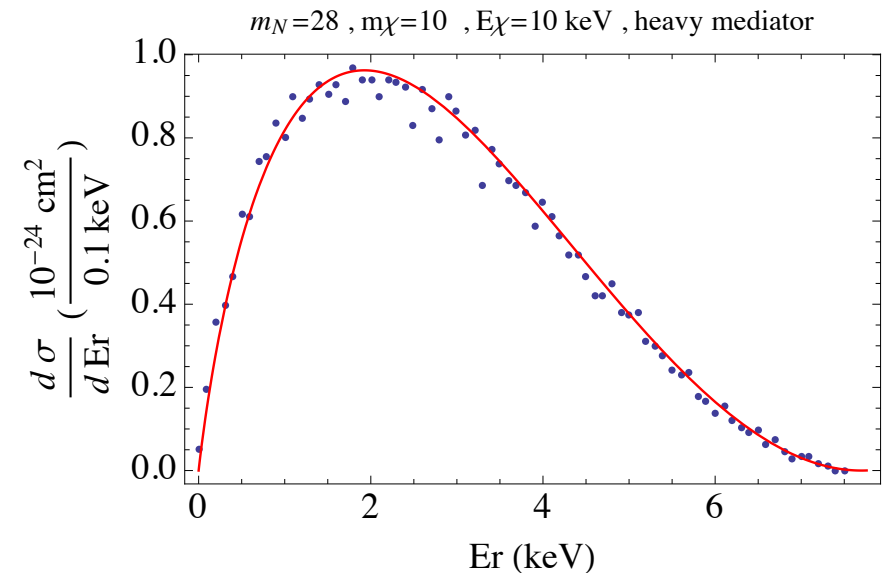
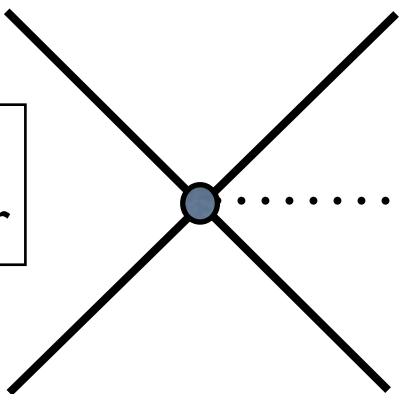
# Recoil energy spectrum

For a given DM energy

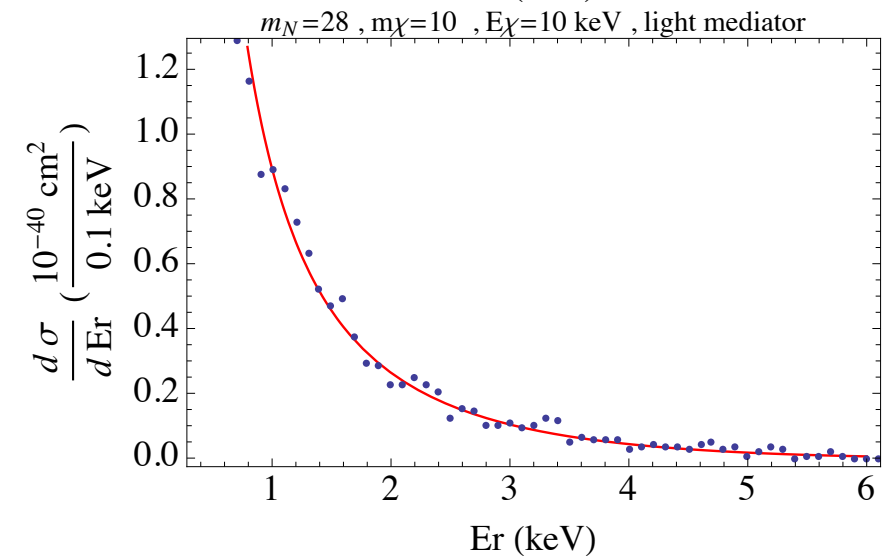
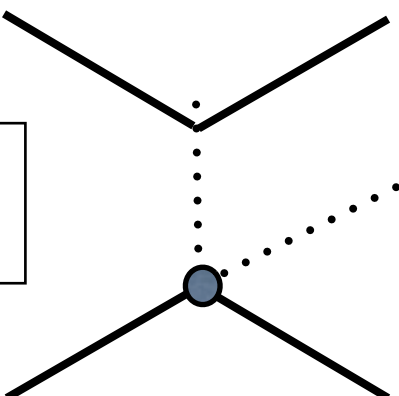
standard 2 to 2  
contact operator



2 to 3  
contact operator



2 to 3  
light mediator



$$\frac{d\sigma}{dE_R} = \frac{|\mathcal{M}|^2}{32\pi m_\chi^2 m_N v^2}$$

$$|\mathcal{M}|^2 \propto \frac{m_N^2 m_\chi^2}{\Lambda^4}$$

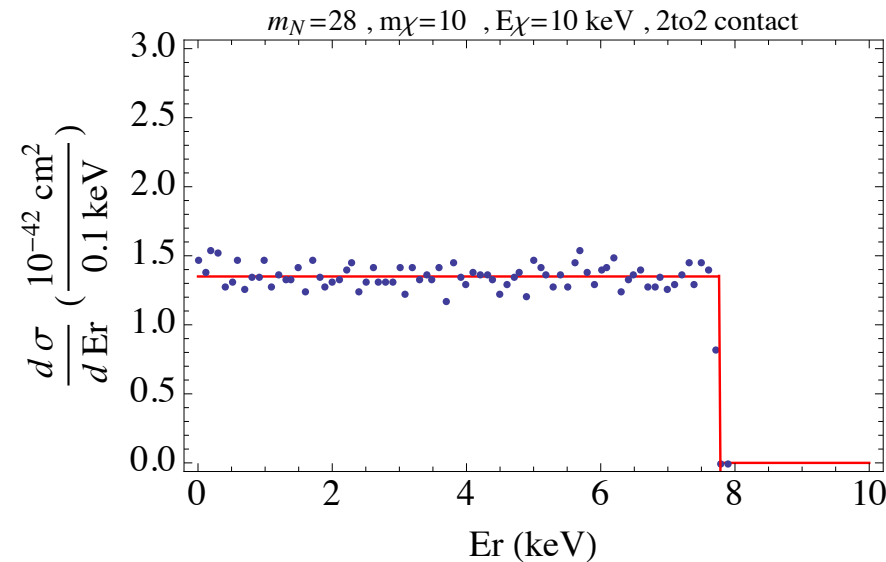
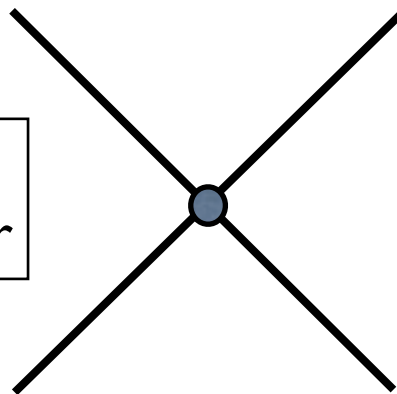
for  $\frac{\bar{\chi}\chi\bar{q}q}{\Lambda^2}$   $\frac{\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q}{\Lambda^2}$

$$E_r^{max} = \frac{2\mu_{N\chi}^2}{m_N} v^2$$

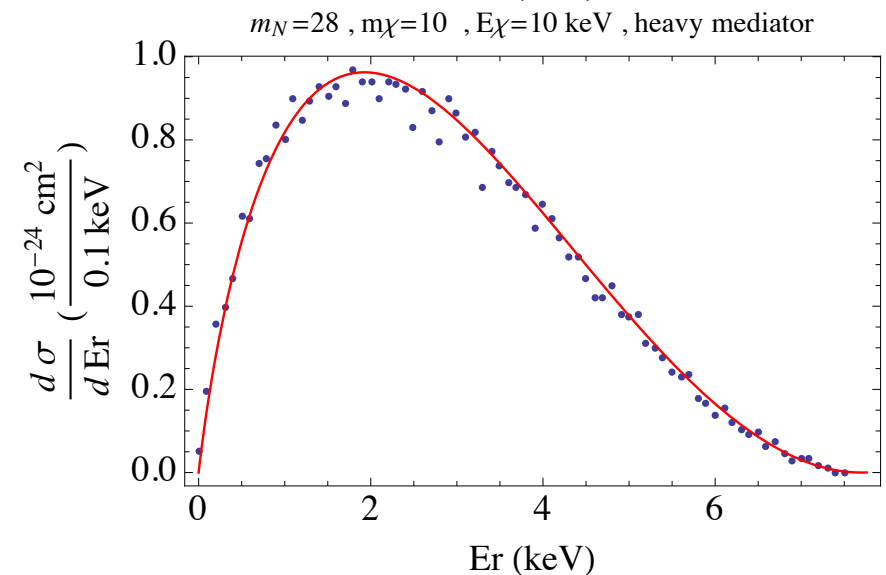
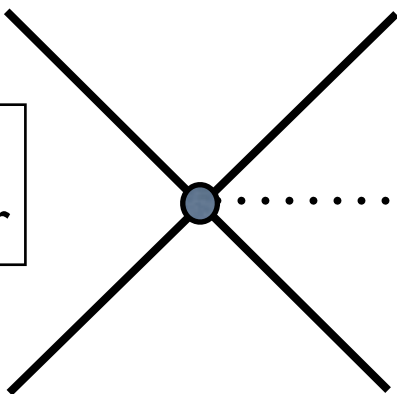
# Recoil energy spectrum

For a given DM energy

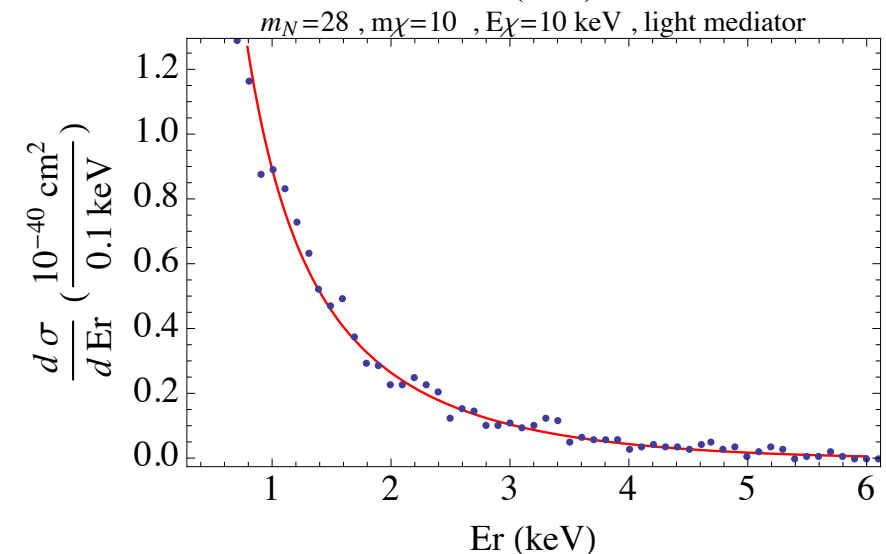
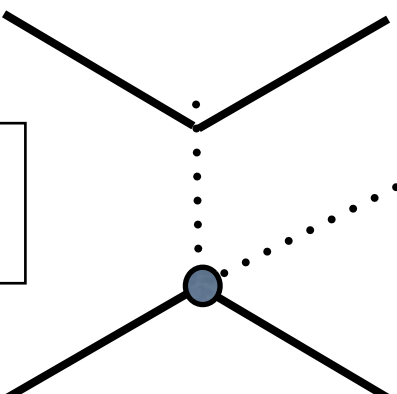
standard 2 to 2  
contact operator



2 to 3  
contact operator



2 to 3  
light mediator



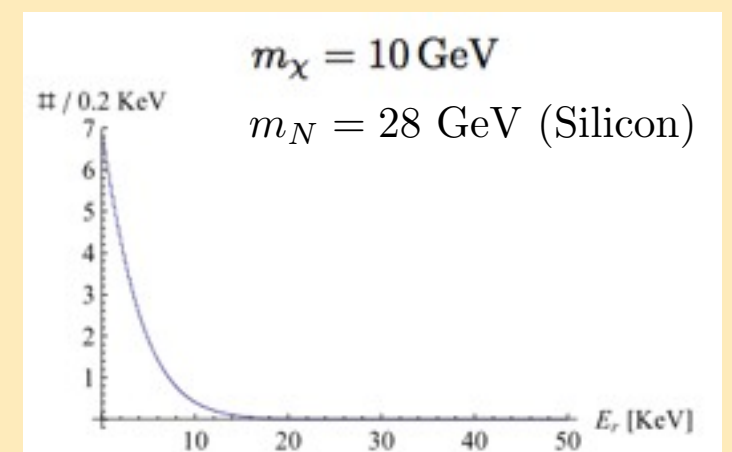
$$\frac{d\sigma}{dE_R} = \frac{|\mathcal{M}|^2}{32\pi m_\chi^2 m_N v^2}$$

$$|\mathcal{M}|^2 \propto \frac{m_N^2 m_\chi^2}{\Lambda^4}$$

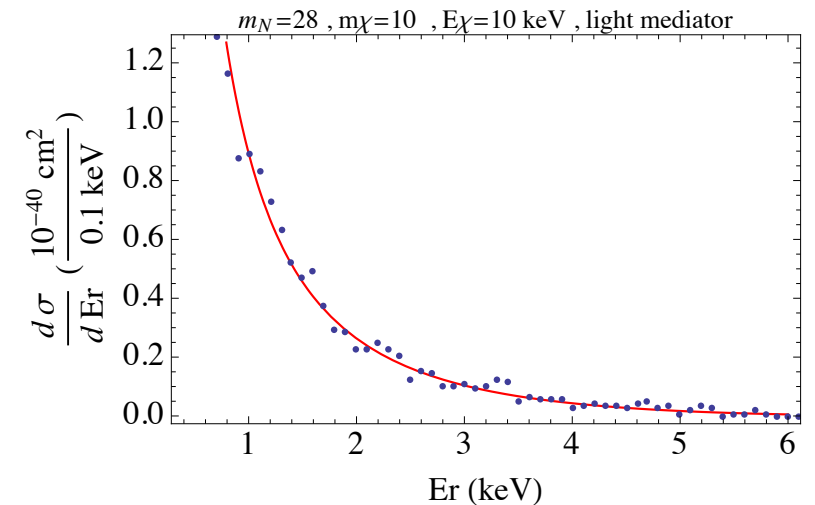
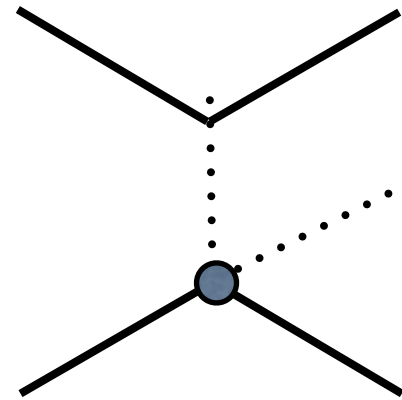
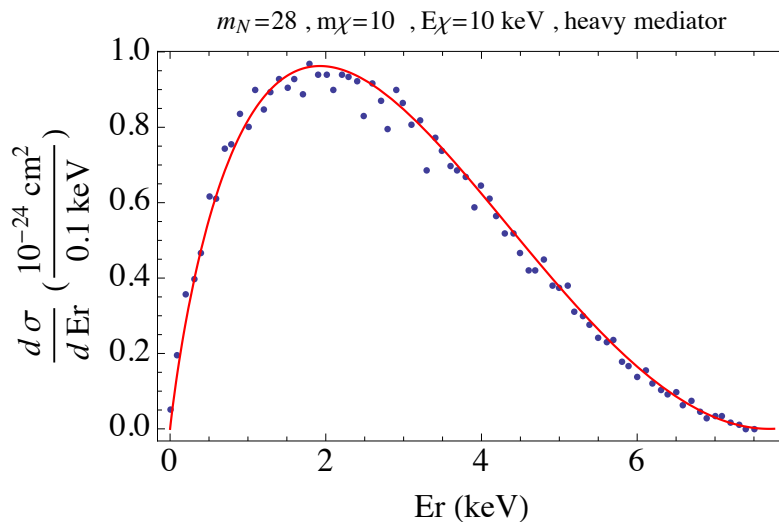
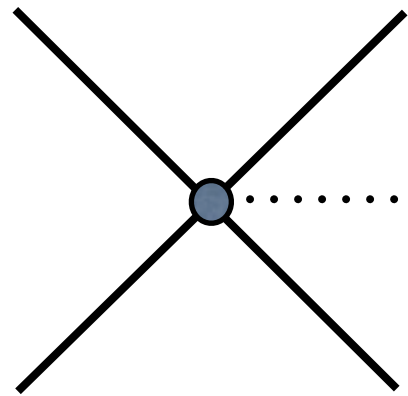
for  $\frac{\bar{\chi}\chi\bar{q}q}{\Lambda^2}$   $\frac{\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q}{\Lambda^2}$

$$E_r^{max} = \frac{2\mu_{N\chi}^2}{m_N} v^2$$

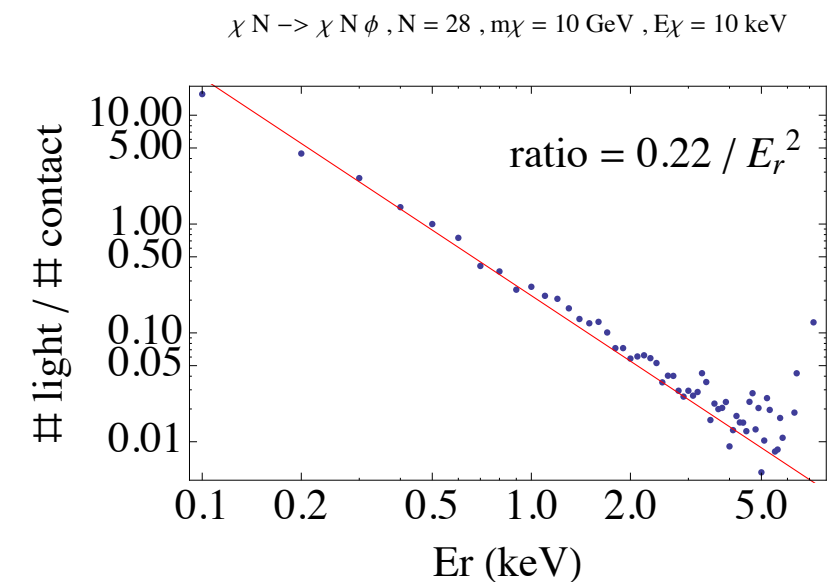
2to2 after f(v) and F



# 2to3 scattering: contact vs. dmDM

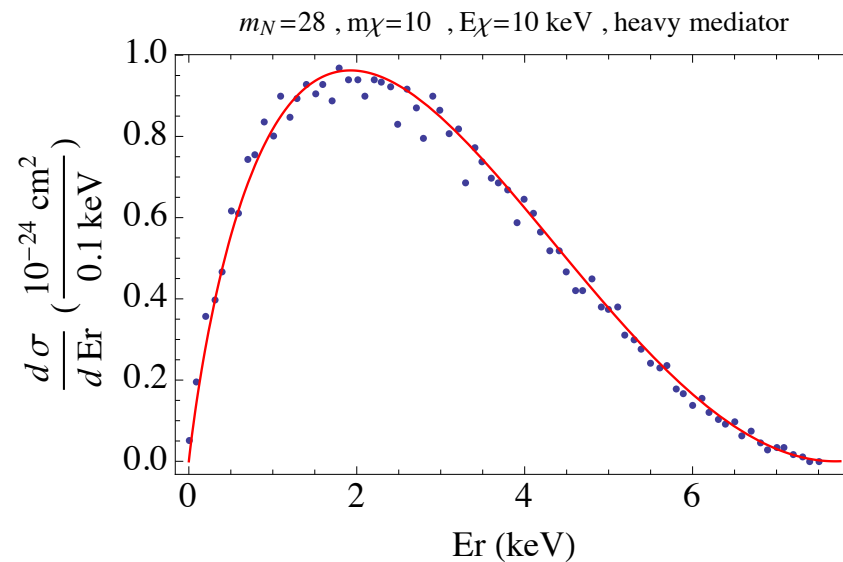
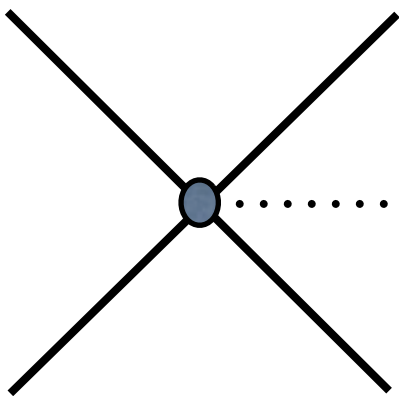


$$\frac{\left. \frac{d\sigma_{2 \rightarrow 3}}{dE_R} \right|_{\text{light}}}{\left. \frac{d\sigma_{2 \rightarrow 3}}{dE_R} \right|_{\text{heavy}}} \propto \frac{m_\Phi^4}{(m_N E_R)^2} \propto \frac{m_\Phi^4}{|\vec{p}_N|^4}$$

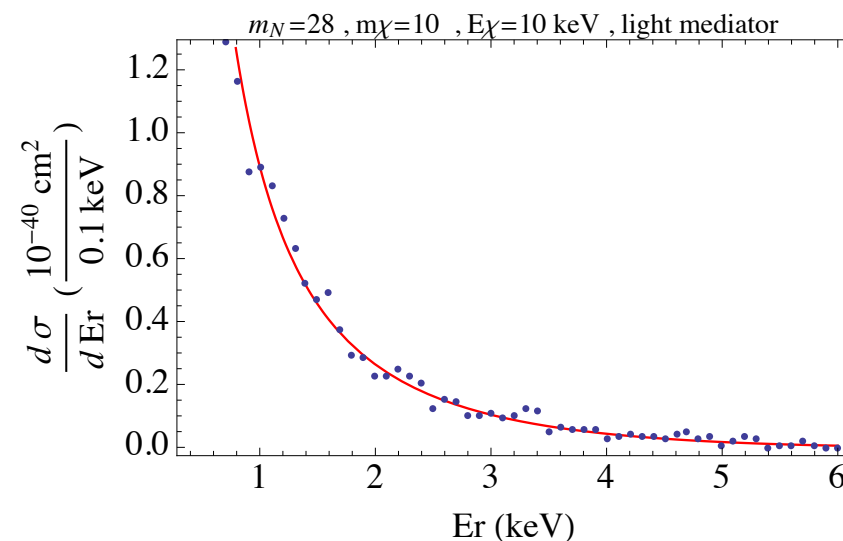
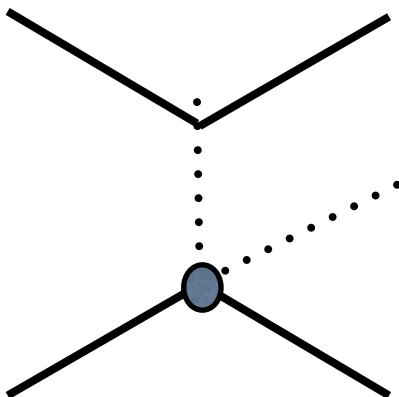


coming from the light mediator's propagator

# Approximation of the spectrum



$$\propto m_N^2 E_R \left( 1 - \sqrt{E_R/E_R^{max}} \right)^2$$



$$\propto E_R^{-1} \left( 1 - \sqrt{E_R/E_R^{max}} \right)^2$$

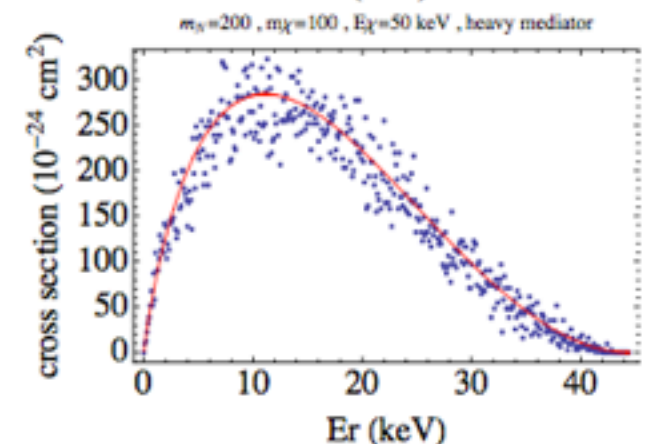
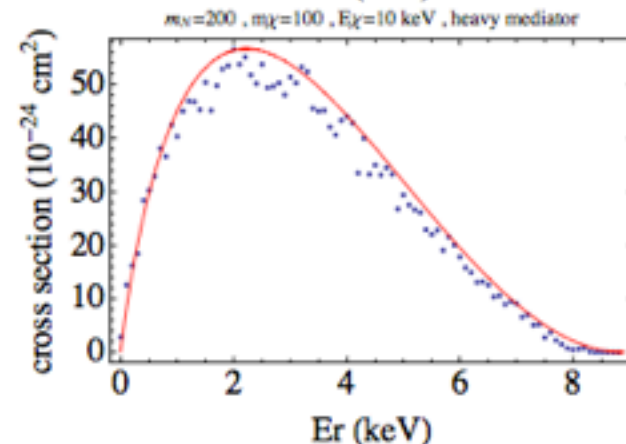
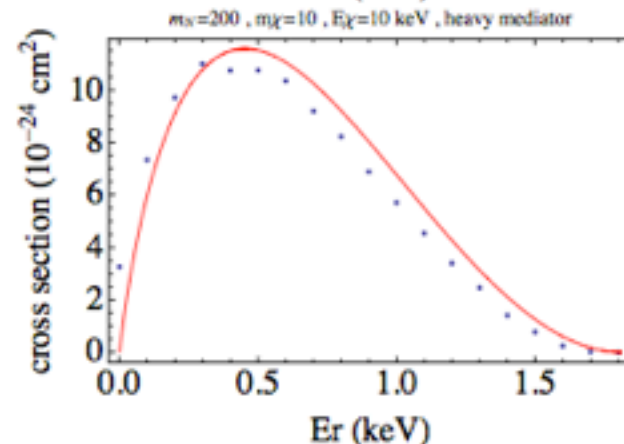
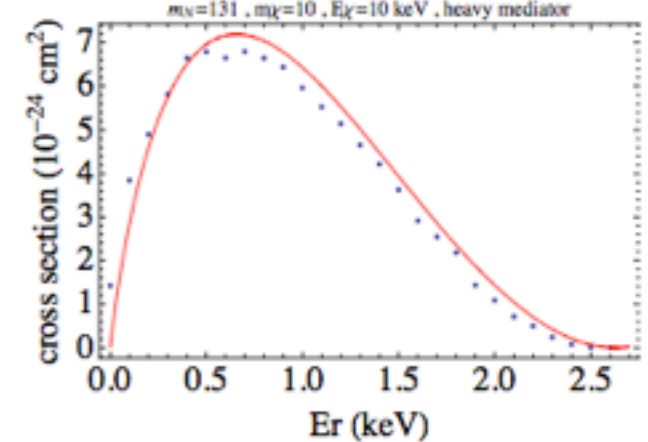
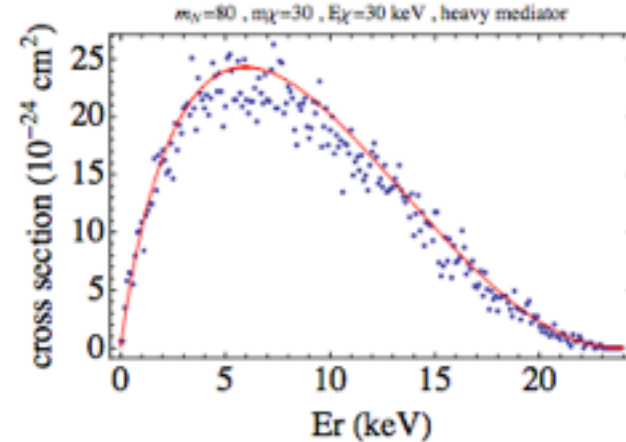
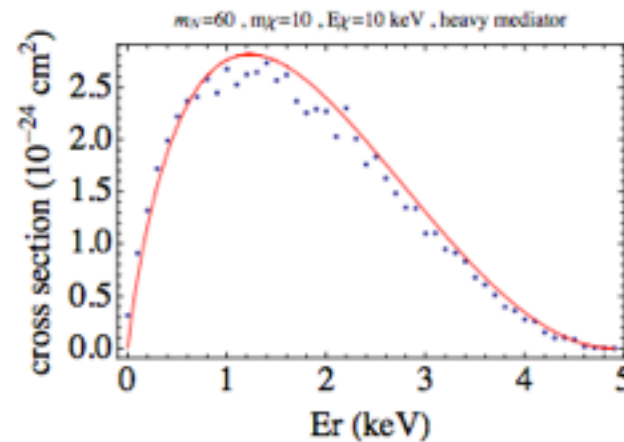
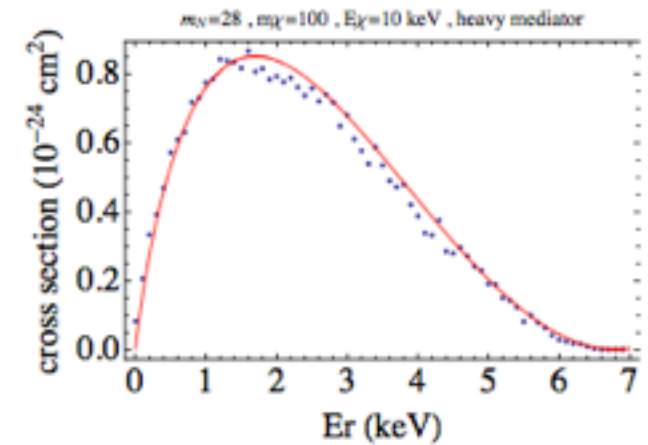
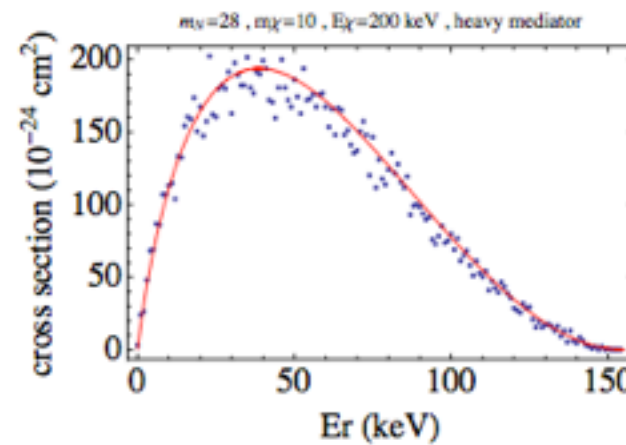
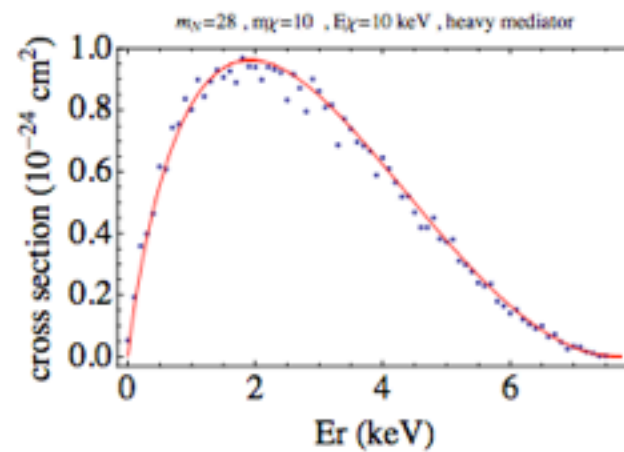
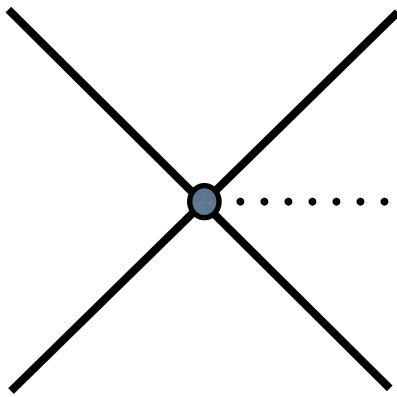
with  $E_R^{max} = \frac{\mu_{\chi N}^2}{2 m_N} v^2$



# A nice description of the Erecoil

$$\frac{d\sigma_{2\rightarrow 3}^{contact}}{dE_R} \simeq constant \times \left(\frac{m_N}{\text{GeV}}\right)^2 \times \left(\frac{E_R}{\text{keV}}\right) \left(1 - \sqrt{E_R / E_R^{max}}\right)^2, \quad E_R^{max} = 2 \frac{\mu_{\chi N}^2}{m_N} v^2$$

$$constant = 2.6 \cdot 10^{-27} (2 \text{ TeV}/m_{\text{med}})^4 (1 \text{ TeV}/\Lambda)^2 \text{ cm}^2/\text{keV}$$

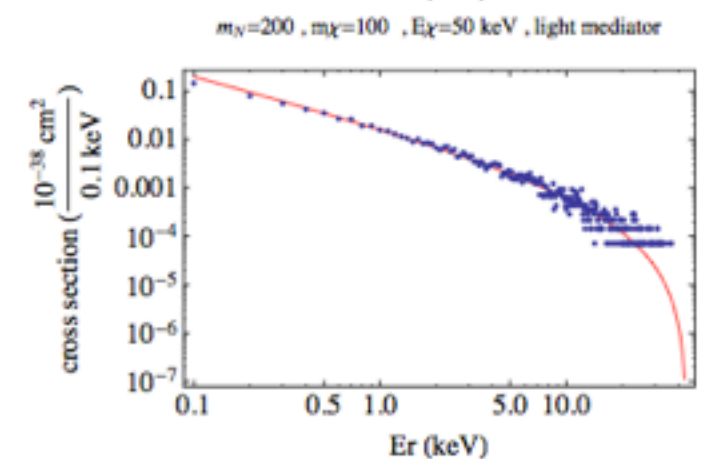
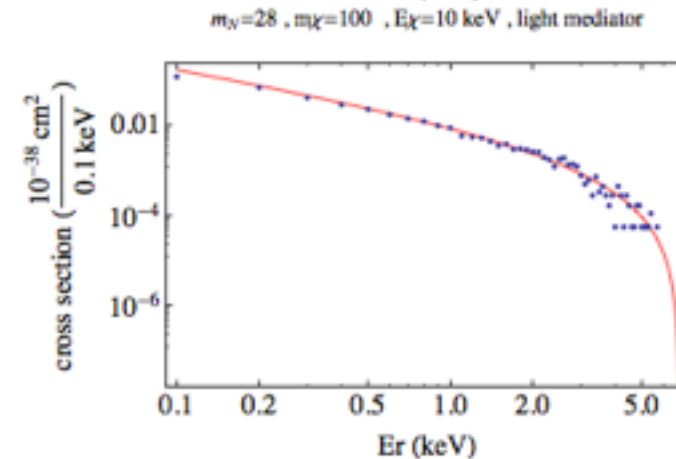
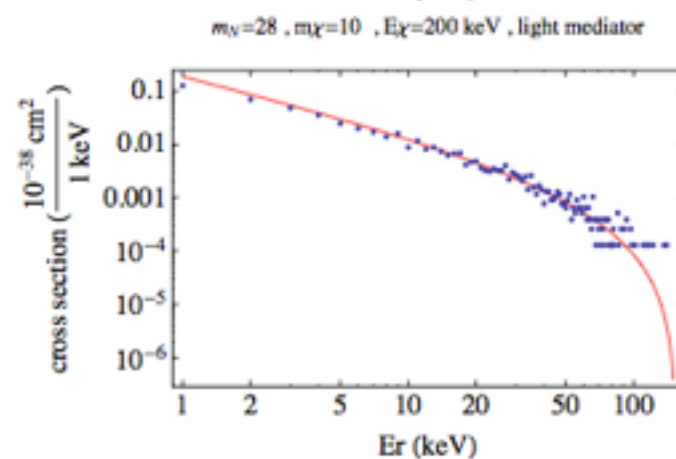
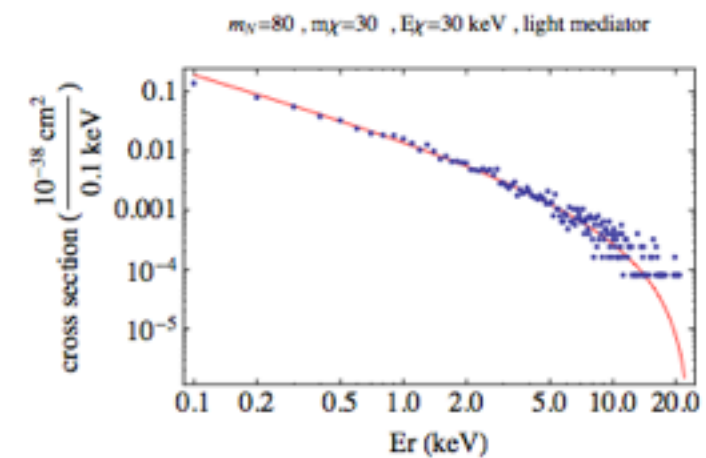
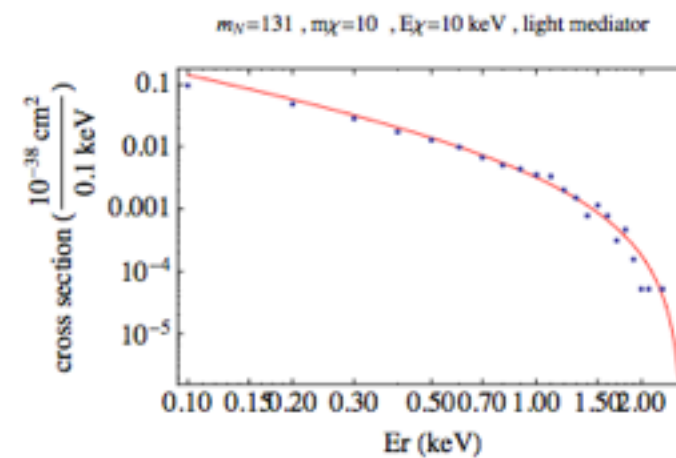
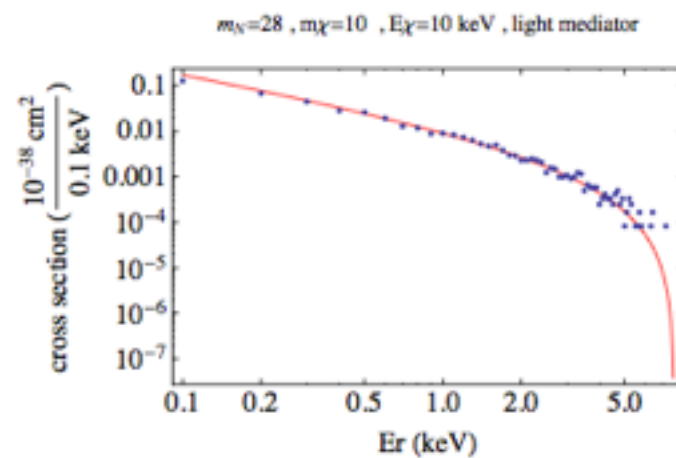
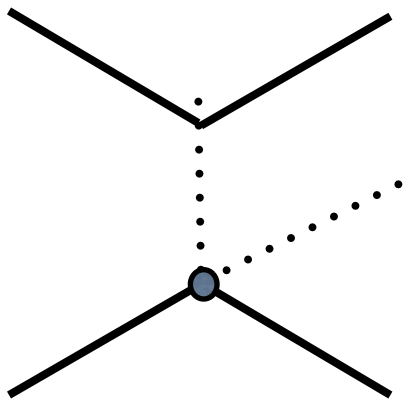




# A nice description of the Erecoil

$$\frac{d\sigma_{2\rightarrow 3}^{light}}{dE_R} \simeq constant \times \left(\frac{E_R}{\text{keV}}\right)^{-1} \left(1 - \sqrt{E_R / E_R^{max}}\right)^2, \quad E_R^{max} = 2 \frac{\mu_{\chi N}^2}{m_N} v^2$$

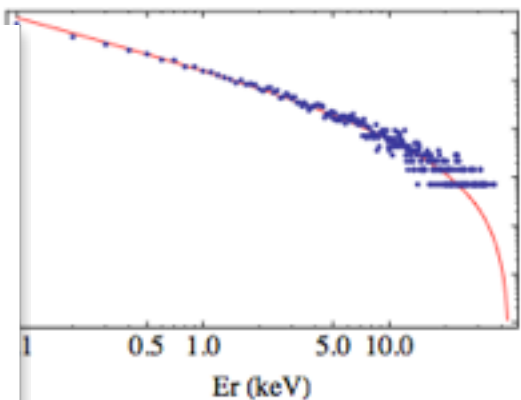
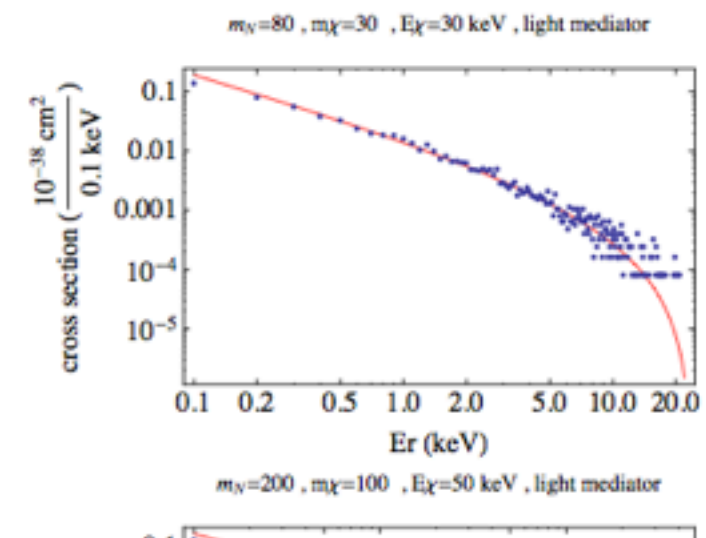
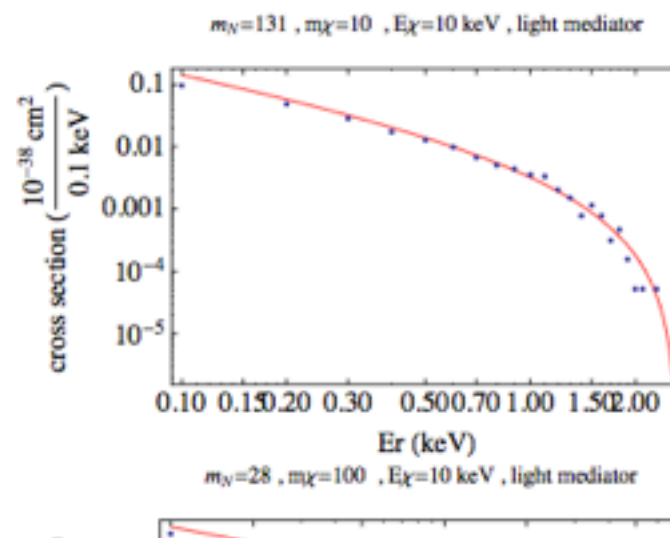
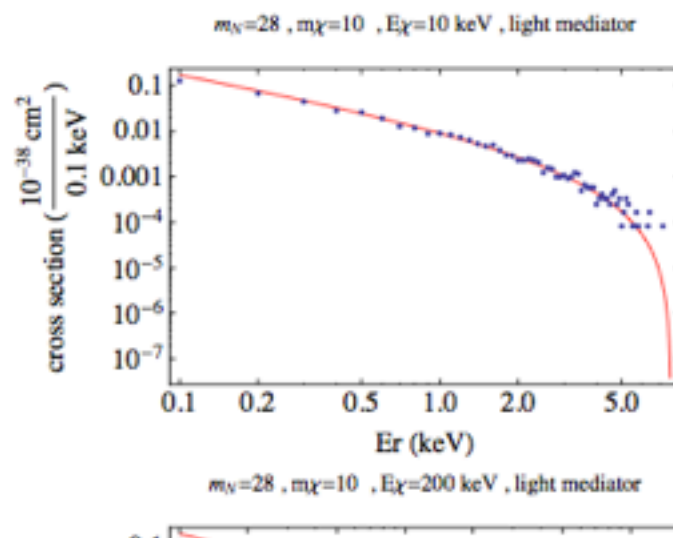
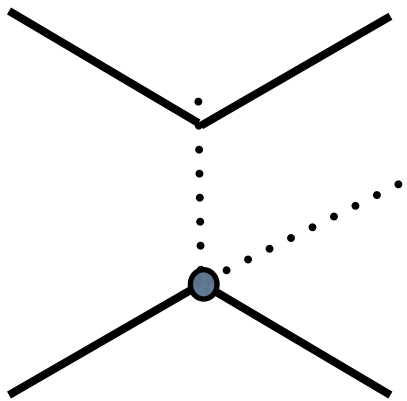
$$constant = 1.3 \cdot 10^{-42} (1 \text{ TeV} / \Lambda)^2 \text{ cm}^2 / \text{keV}$$



# A nice description of the Erecoil

$$\frac{d\sigma_{2\rightarrow 3}^{light}}{dE_R} \simeq constant \times \left(\frac{E_R}{\text{keV}}\right)^{-1} \left(1 - \sqrt{E_R/E_R^{max}}\right)^2, \quad E_R^{max} = 2 \frac{\mu_{\chi N}^2}{m_N} v^2$$

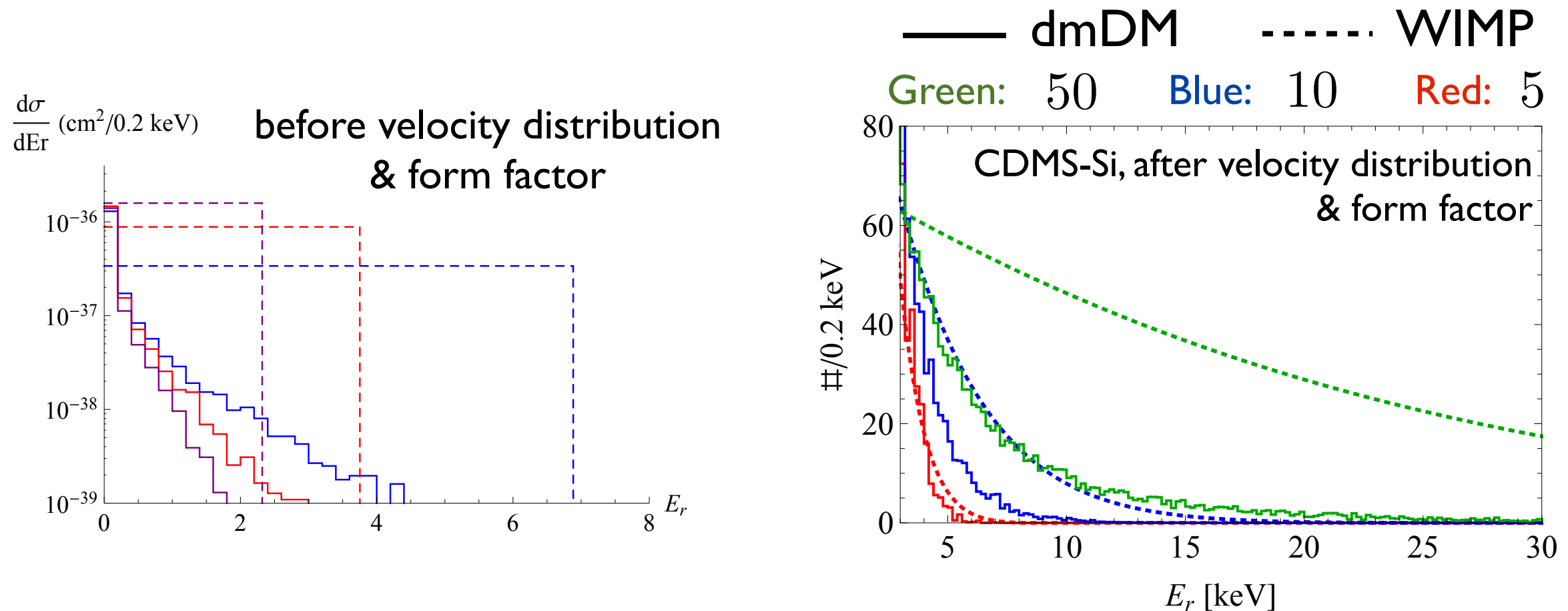
$$constant = 1.3 \cdot 10^{-42} (1 \text{ TeV}/\Lambda)^2 \text{ cm}^2/\text{keV}$$



Three ingredients give the spectrum

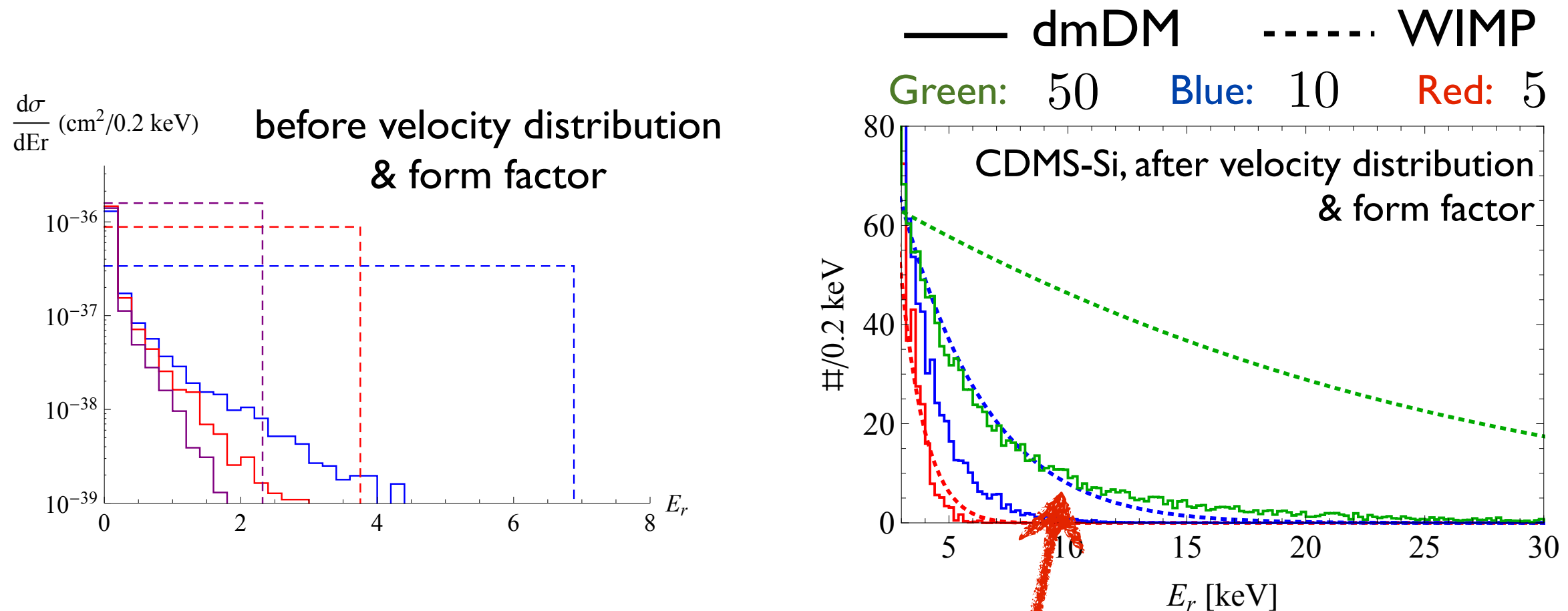
- I. phase space with  $\phi$  carrying away some energy
- II.  $E_R^{max}$  relates to the DM-nucleus mass
- III.  $E_R^{-2}$  from the propagator of light mediator

# Mappings between 2to2 & 2to3



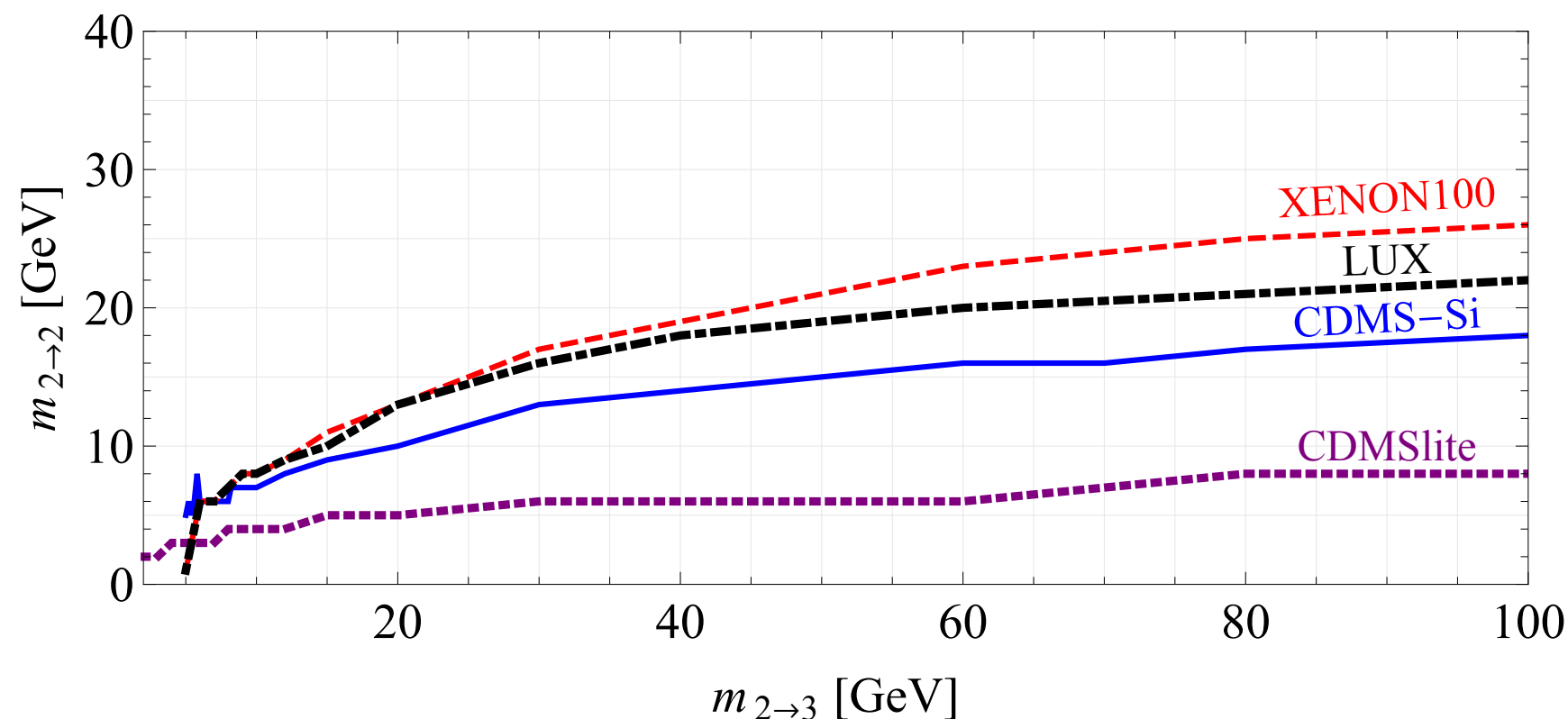
- lack of events makes it hard to distinguish the shape difference in detail
- heavy dmDM looks like a light WIMP DM
- since the  $m_\chi$  of dmDM only shows up in  $\mu_{\chi N}$  of the spectrum, **the spectrum is insensitive to the DM mass when the true  $m_\chi \gg \mu_{\chi N}$**

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- since the  $m_\chi$  of dmDM only shows up in  $\mu_\chi N$  of the spectrum, **the spectrum is insensitive to the DM mass when the true  $m_\chi \gg \mu_\chi N$**

# Pseudo-light Dark Matter



- 100 GeV DM fakes a 10 GeV WIMP
- different masses obtained by different experiments

A single experiment cannot get the mass right.  
Multiple experiments are necessary for the mass measurement.

# Pseudo Light Dark Matter at direct detections

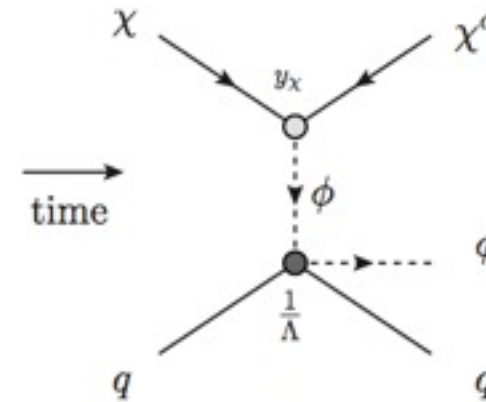
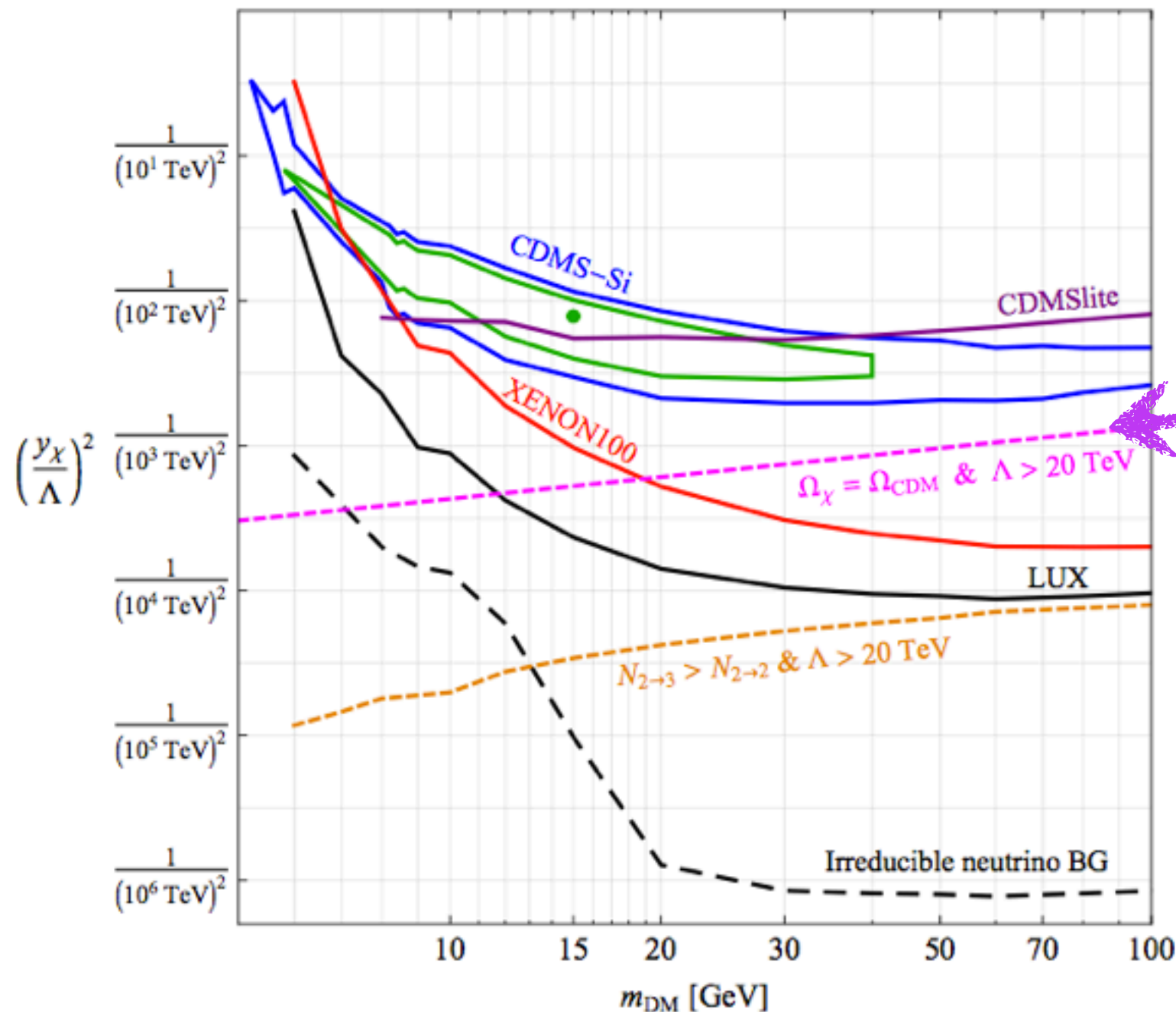




# Pretty **L**ame **D**ark **M**atter for direct detections

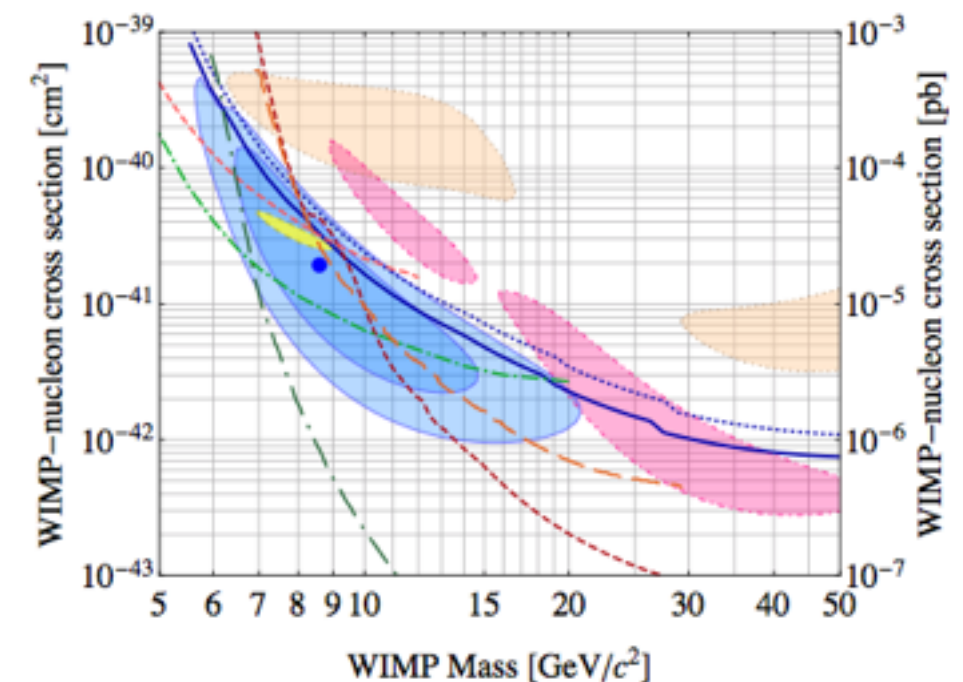


# Interaction vs. mass



$$\sigma \propto \left| \frac{y_\chi}{\Lambda} \right|^2$$

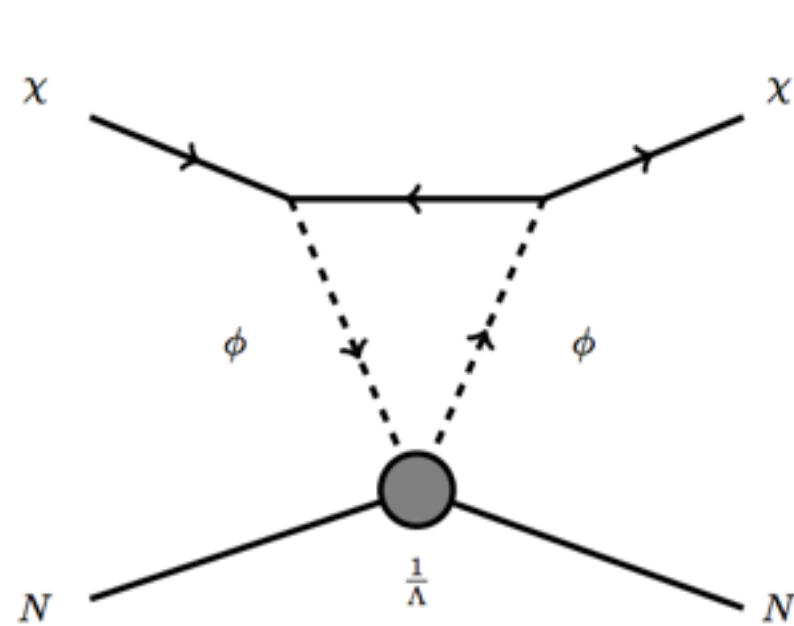
for DM as a thermal relic  
 $\Lambda > 20 \text{ TeV}$  is given by  
 the cooling constraints





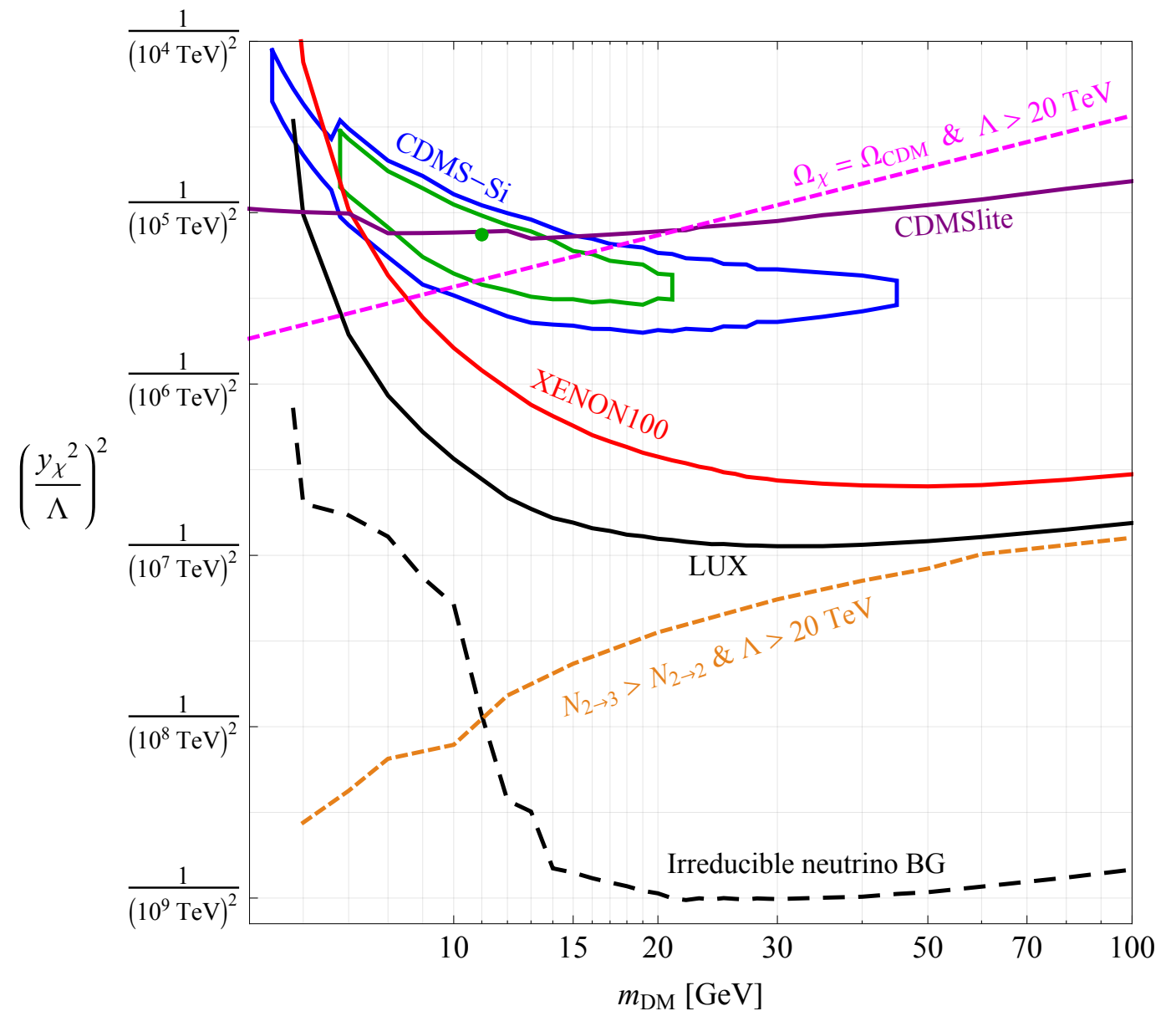
# Loop-induced 2 to 2 process

The simplest model generates a 2 to 2 scattering



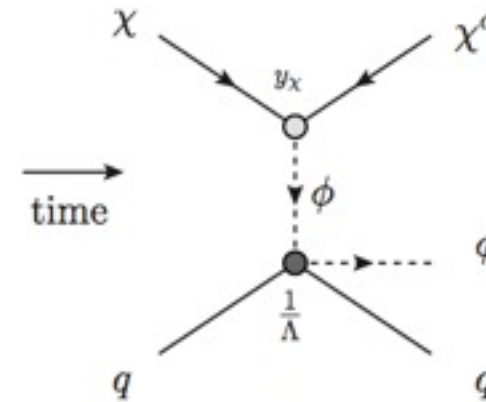
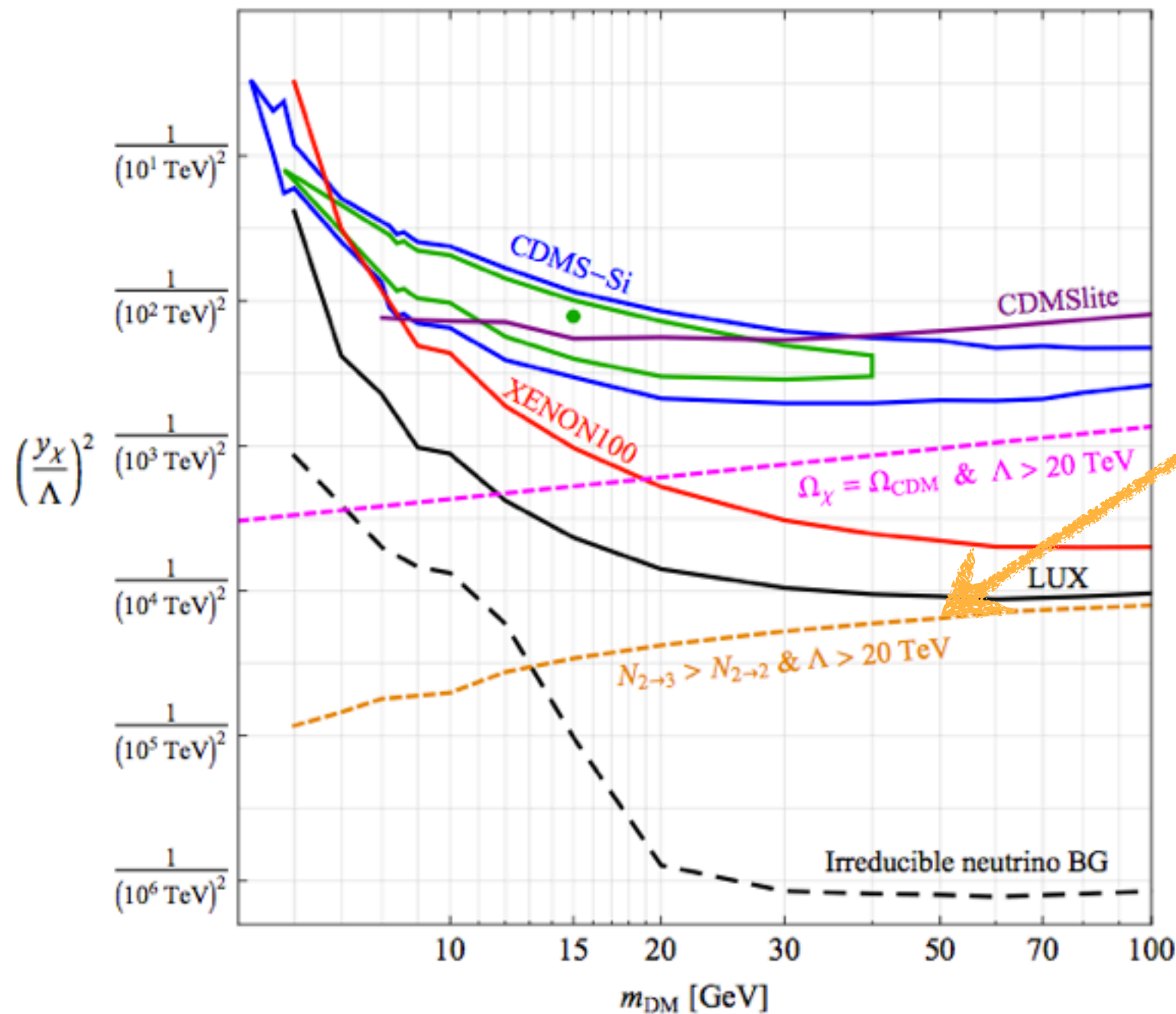
$$\approx \frac{y_\chi^2}{2\pi^2} \frac{1}{\Lambda q} (\bar{\chi} \chi \bar{N} N)$$

$$q = \sqrt{2m_N E_R}$$



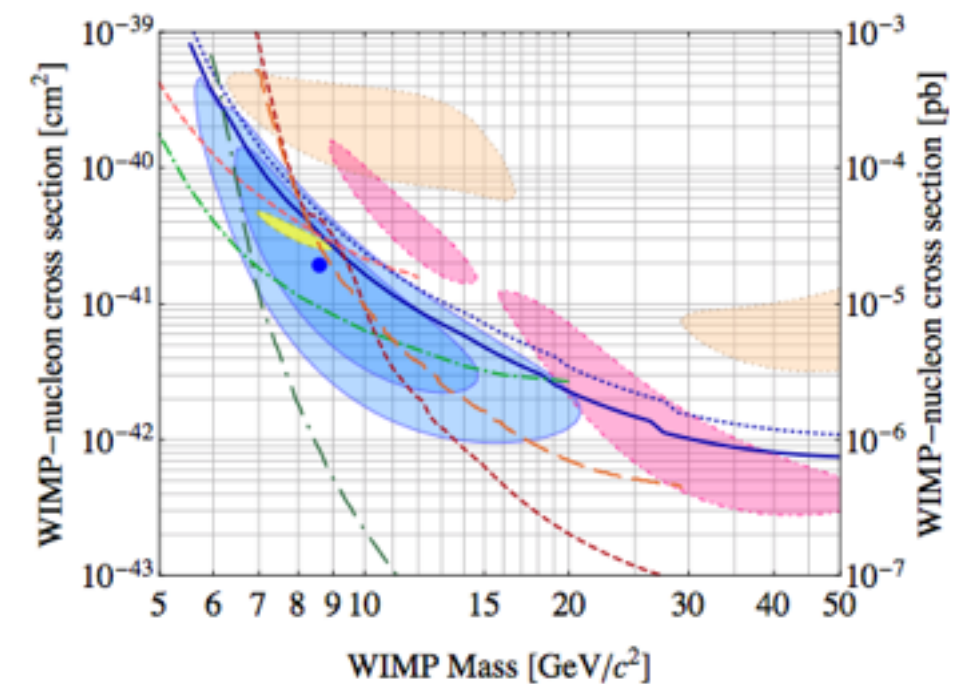
Can be avoided in the **heavy**light model

# Interaction vs. mass

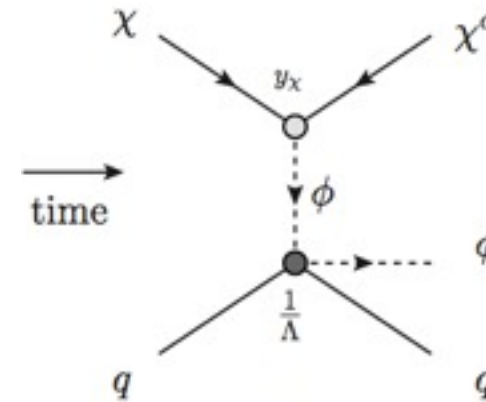
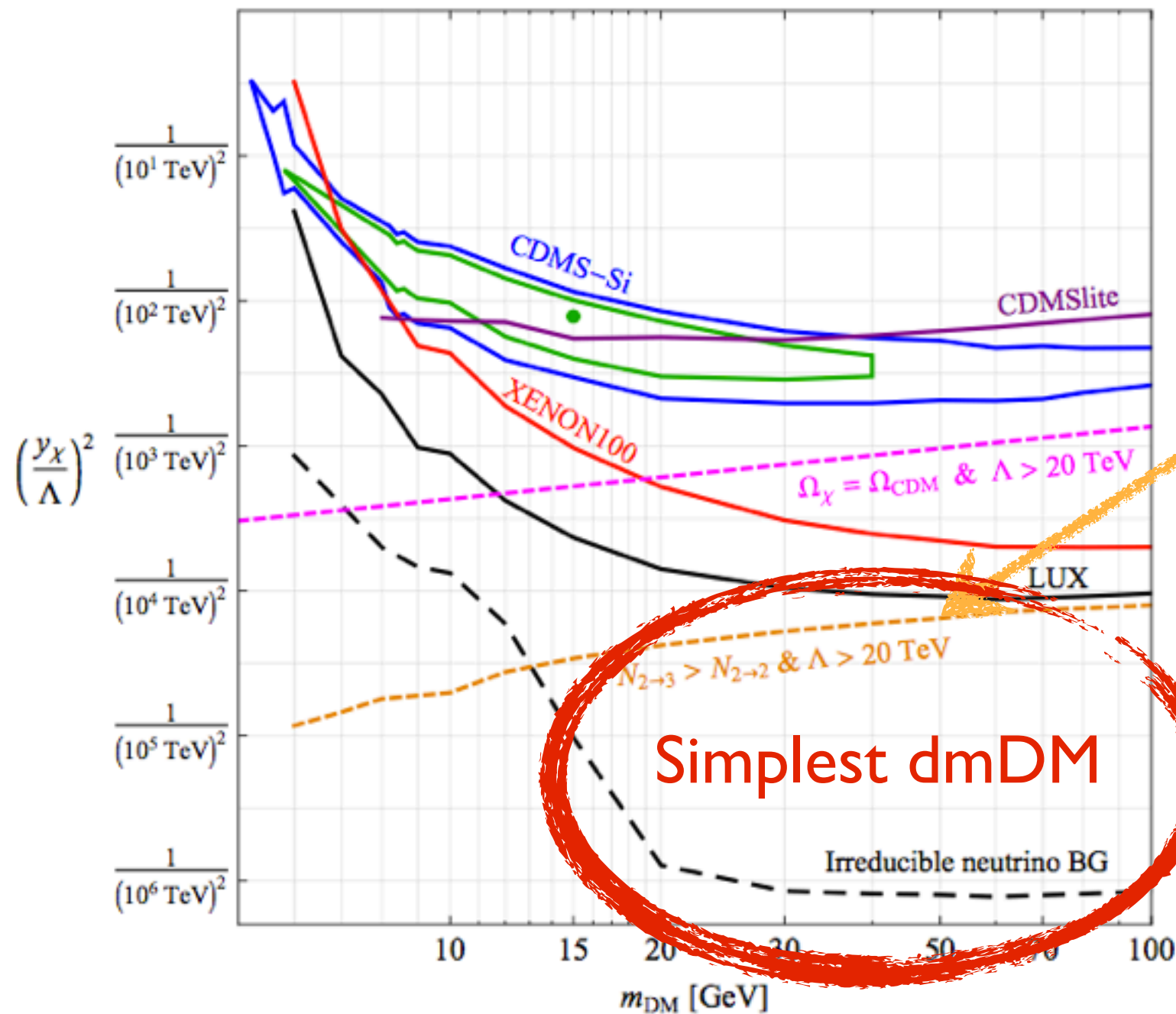


$$\sigma \propto \left| \frac{y_\chi}{\Lambda} \right|^2$$

for 2 to 3 > 2 to 2  
 $\Lambda > 20 \text{ TeV}$  is given by  
 the cooling constraints

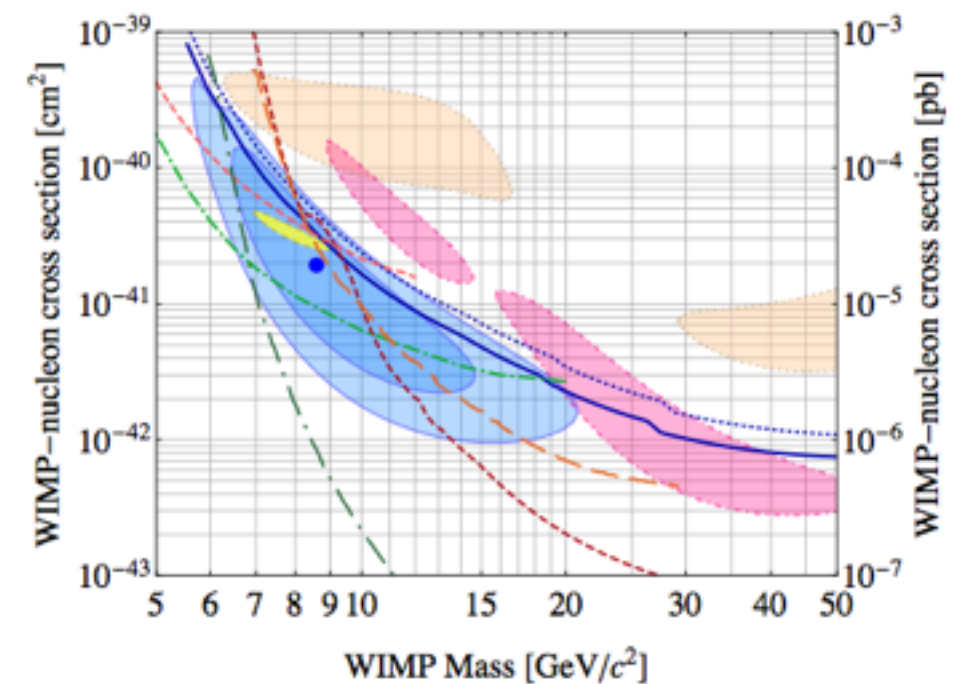


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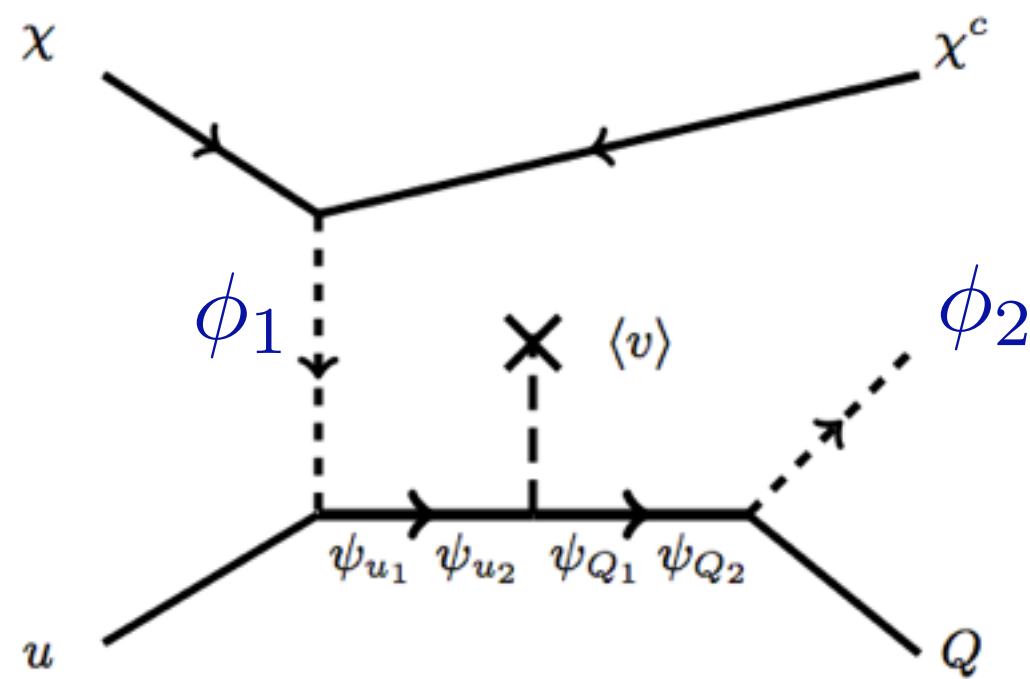


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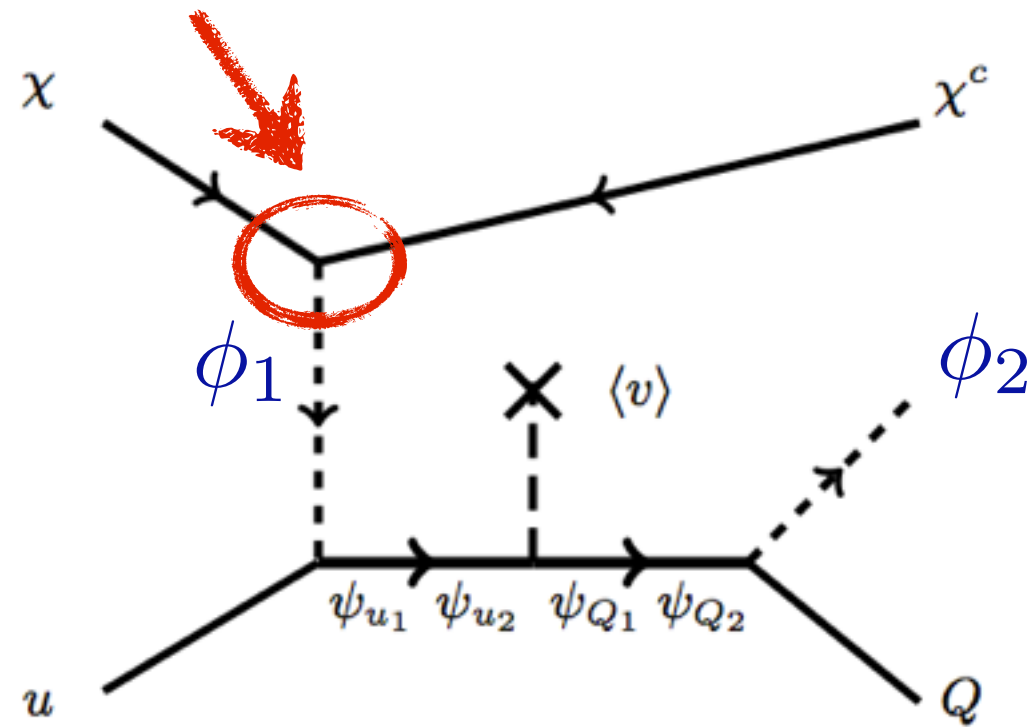


# Various Constraints on dmDM



# Various Constraints on dmDM

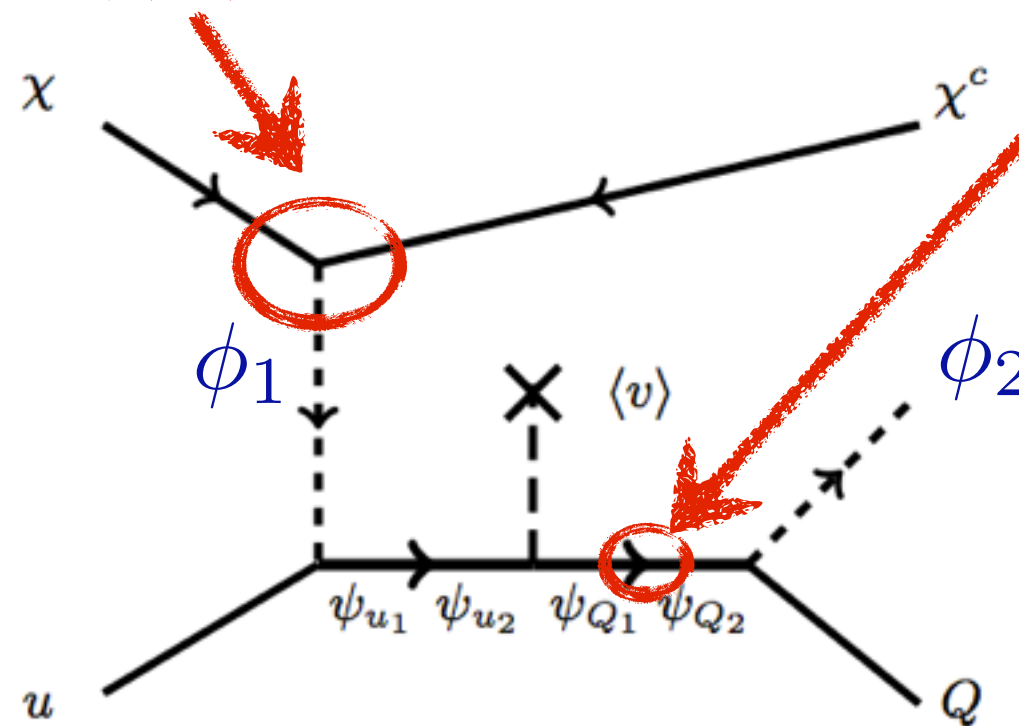
DM self-interaction bounds  
DM relic abundance  $\Omega_\chi$



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DM self-interaction bounds  
DM relic abundance  $\Omega_\chi$

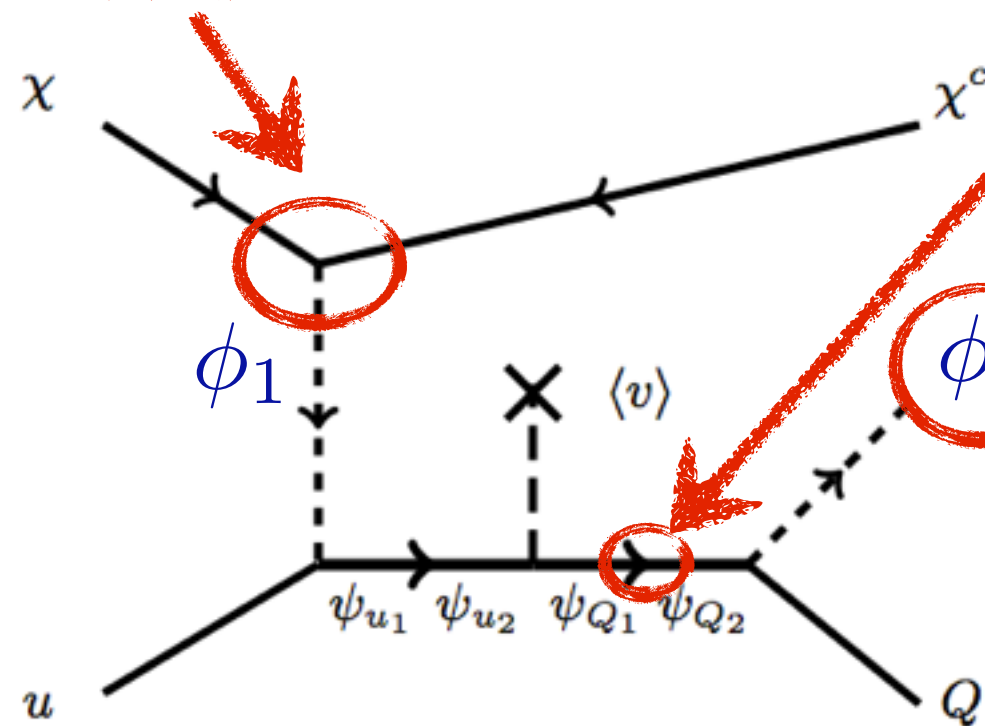
LHC bounds



# Various Constraints on dmDM

DM self-interaction bounds  
DM relic abundance  $\Omega_\chi$

LHC bounds



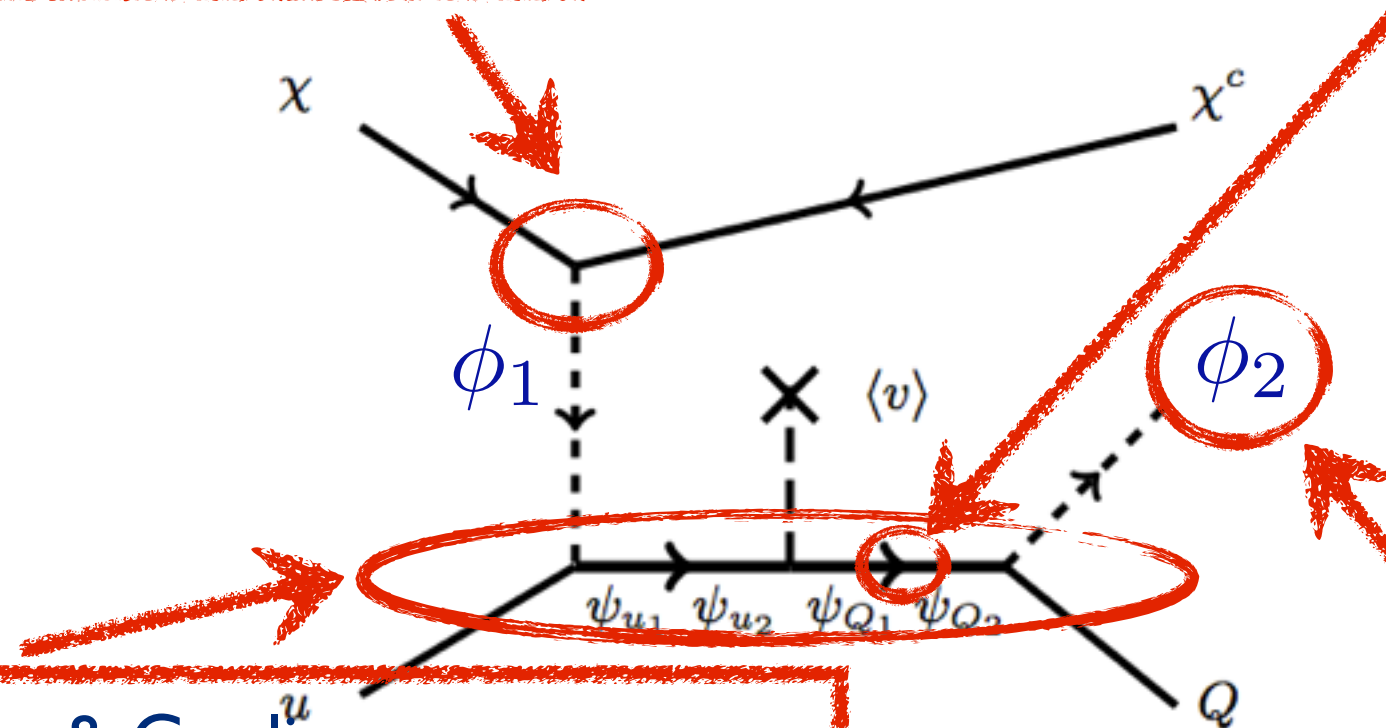
$\Omega_\phi$   
BBN:  $N_{\text{eff}}$   
Structure Formation



# Various Constraints on dmDM

DM self-interaction bounds  
DM relic abundance  $\Omega_\chi$

LHC bounds

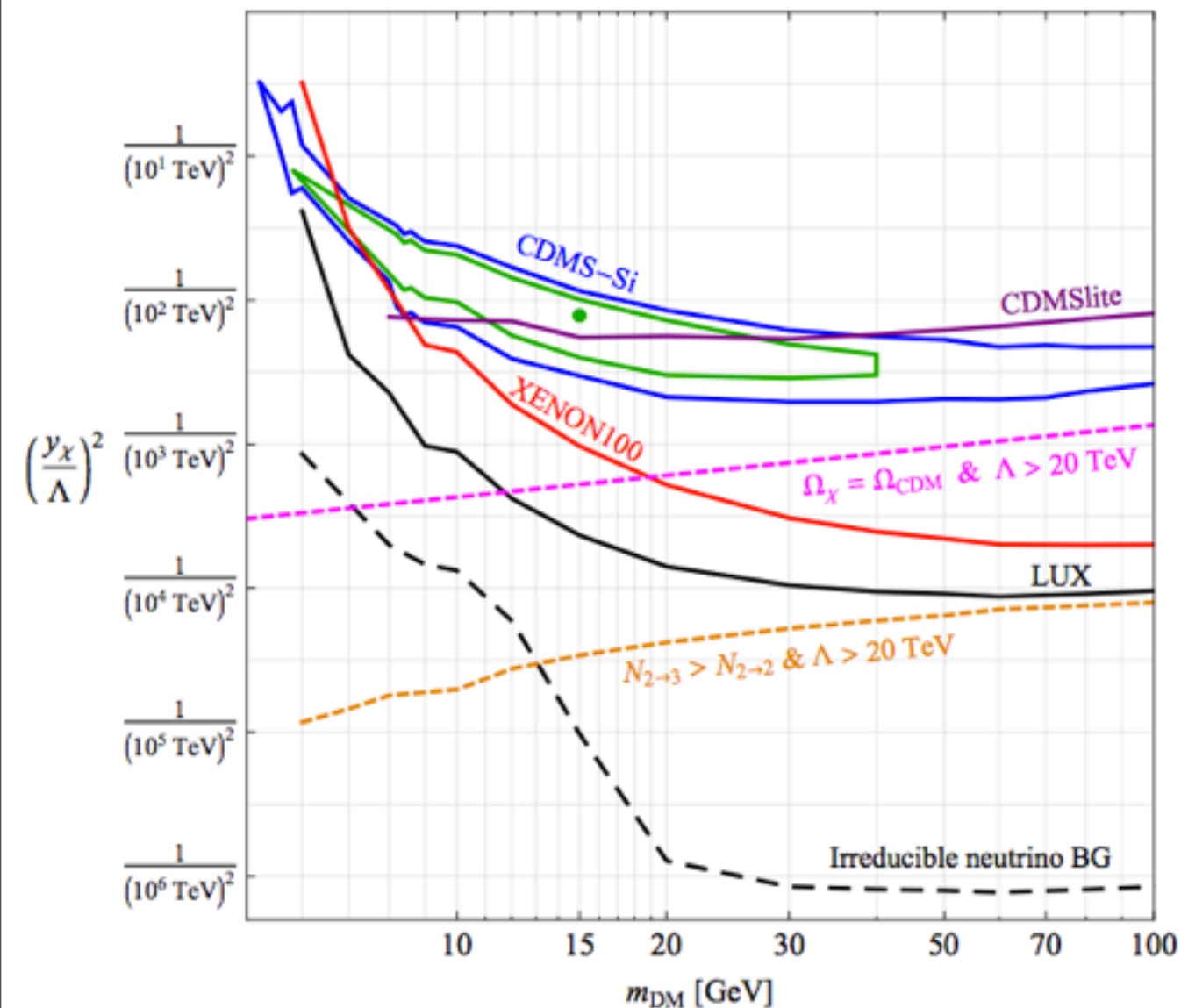


Solar Heat Transfer & Cooling  
Supernova Cooling  
White Dwarf Cooling  
Neutron Star Cooling  
Fixed Target Experiments & Beam Dumps  
Meson Decays  
 $Z\phi\phi$  coupling

$\Omega_\phi$   
BBN:  $N_{\text{eff}}$   
Structure Formation



# Various Constraints on dmDM



$$\frac{|\phi|^2 \bar{Q} q}{\Lambda} \quad y_\chi \quad m_\phi$$

We will only discuss the  $\Lambda$  bounds that are stronger than  $\Lambda > 10 \text{ TeV}$  in this talk

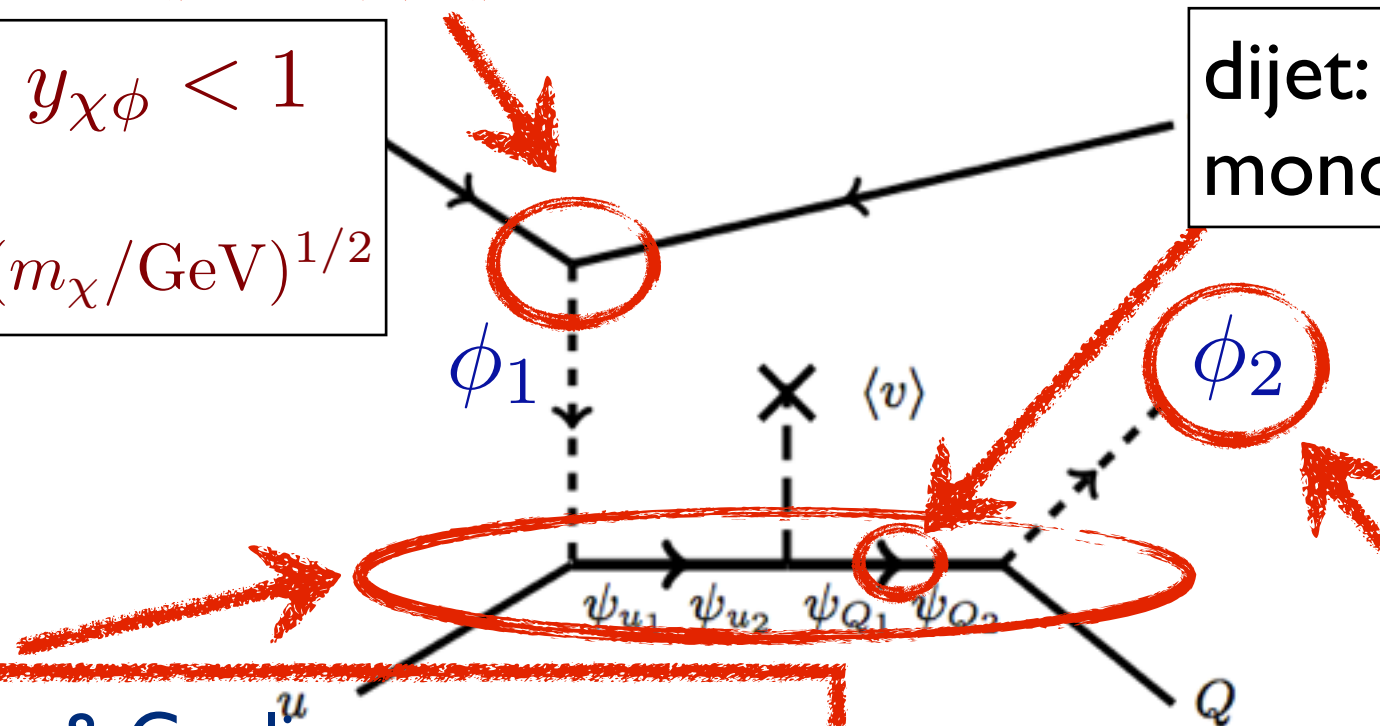
# Various Constraints on dmDM

DM self-interaction bounds  
DM relic abundance  $\Omega_\chi$

bullet cluster:  $y_{\chi\phi} < 1$   
thermal relic:  
 $y_\chi \approx 2.7 \times 10^{-3} (m_\chi/\text{GeV})^{1/2}$

LHC bounds

dijet:  $M_Q > 1.5 \text{ TeV}$   
monojet:  $\Lambda > 6 \text{ TeV}$



Solar Heat Transfer & Cooling  
Supernova Cooling  
White Dwarf Cooling  
Neutron Star Cooling  
Fixed Target Experiments & Beam Dumps  
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$\Lambda$  bounds are weaker than 10 TeV

$\Omega_\phi$   
BBN:  $N_{\text{eff}}$   
Structure Formation

# Cosmological Constraints : $N_{\text{eff}}$

$\phi$  decoupled from thermal bath at  $T_{\phi}^{\text{freeze}} > 10 \text{ MeV} \left( \frac{\Lambda}{10 \text{ TeV}} \right)^{2/3}$

If the decoupling happens just before the BBN,  $N_{\text{eff}}$  has a  $2\sigma$  deviation from the current measurement  $N_{\text{eff}} = 3.36^{+0.68}_{-0.64}$  (95 % CL)<sub>Planck+WMAP+HighL</sub>

This can be relaxed when having  $\phi$  as a real scalar charged under a  $Z_4$  symmetry  $\phi \rightarrow -\phi, \chi \rightarrow e^{i\pi/2}\chi$  so the deviation becomes small

# $\Omega_\phi$ & the structure formation

- The  $\phi$  density gives  $\Omega_\phi h^2 \equiv 7.83 \times 10^{-2} \frac{g_\phi}{g_{*S}} \frac{m_\phi}{\text{eV}} \quad g_\phi = 2, \quad g_{*S} \simeq 12$

This requires  $m_\phi < \text{eV}$  for having no significant contribution to the density if  $\phi$  does not decay

- $\phi$  was a collisionless particle during the structure formation ( $\sim 10$  eV). It only generates Landau damping to the primordial density fluctuations with a FS-length similar to neutrinos

$$\lambda_{FS, \phi} \simeq 20 \text{ Mpc} \left( \frac{m_\phi}{10 \text{ eV}} \right)^{-1}$$

$\phi$  satisfies similar constraints as a light sterile neutrino

- Can also make  $\phi$  decay by having  $\phi F_{\mu\nu} \tilde{F}^{\mu\nu} / \Lambda$

# Cooling Constraints



supernovae



white dwarf



neutron star



the Sun

# Stellar cooling: generalities

- If  $m_\phi \lesssim T$  the scalar can be produced inside of stars.
- A production process  $X_1 X_2 \rightarrow \phi + \dots$  yields  $r_\phi = n_{X_1} n_{X_2} c \sigma_{\phi\text{prod}}$   $\phi$ s per unit volume per unit time.
- If we know the radial profiles of stellar density, temperature and composition we can find the total  $\phi$  production rate for the star (*assuming  $\phi$  does not significantly alter stellar evolution*).
- In the absence of significant  $\phi$ -destroying processes, this is equal to the equilibrium total  $\phi$  loss rate.



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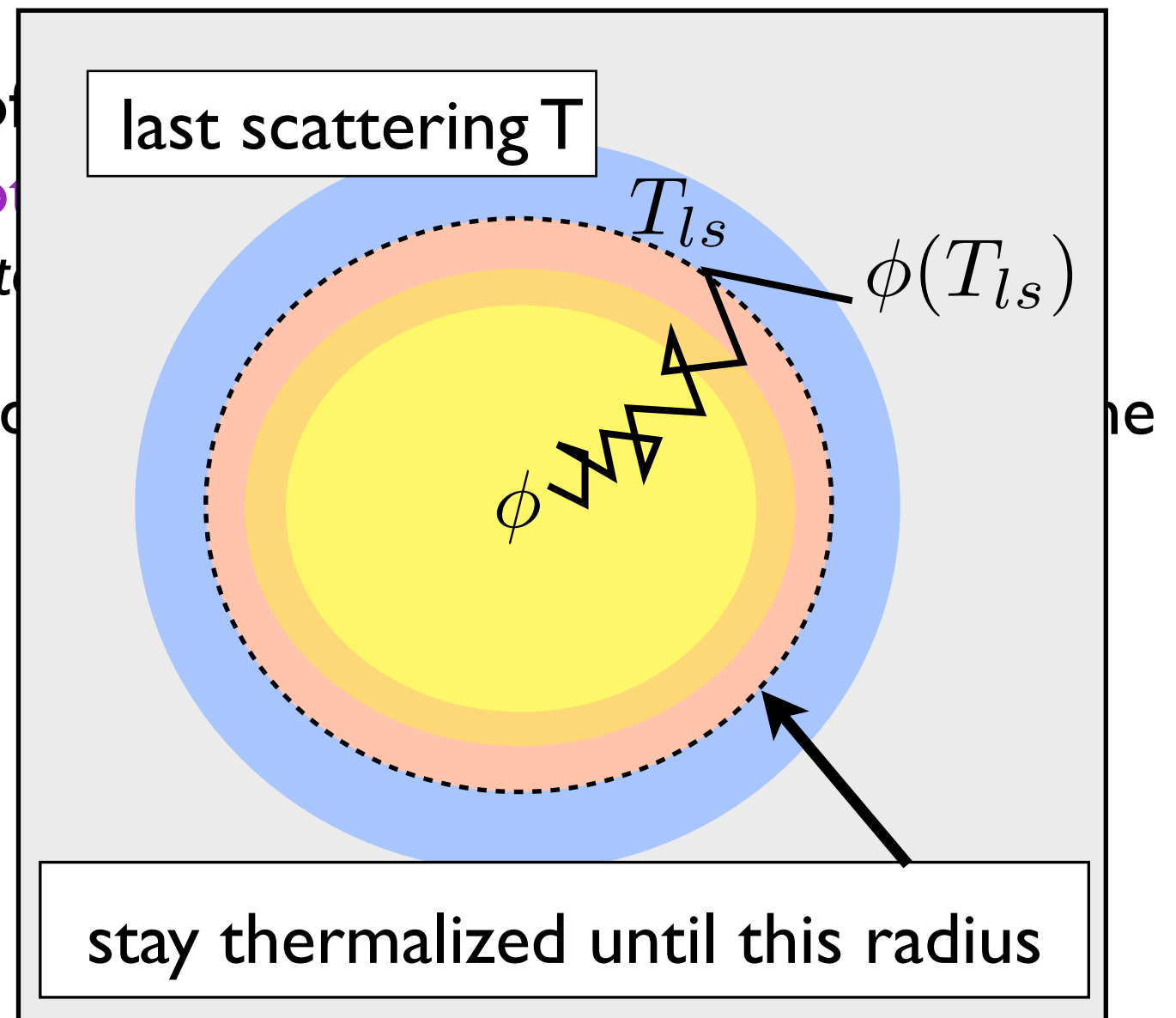
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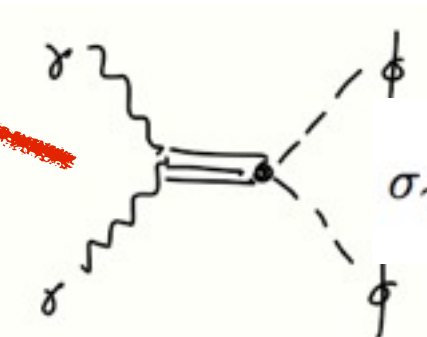
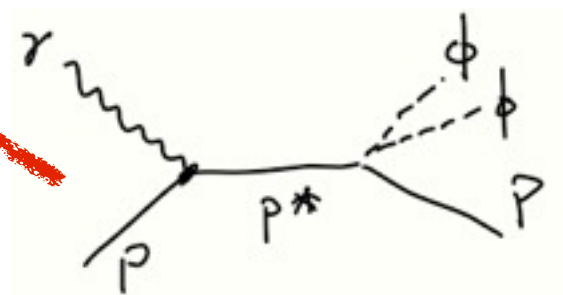
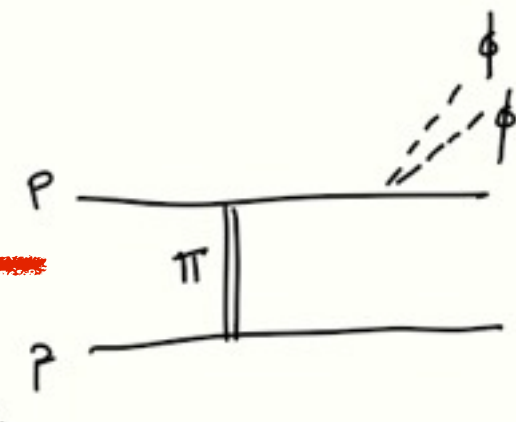
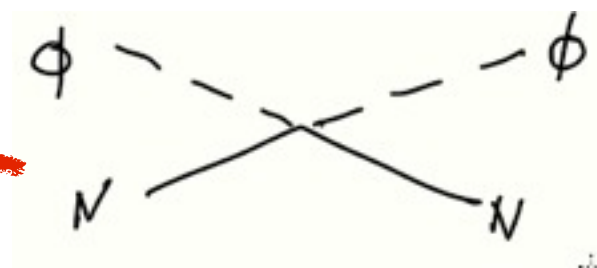
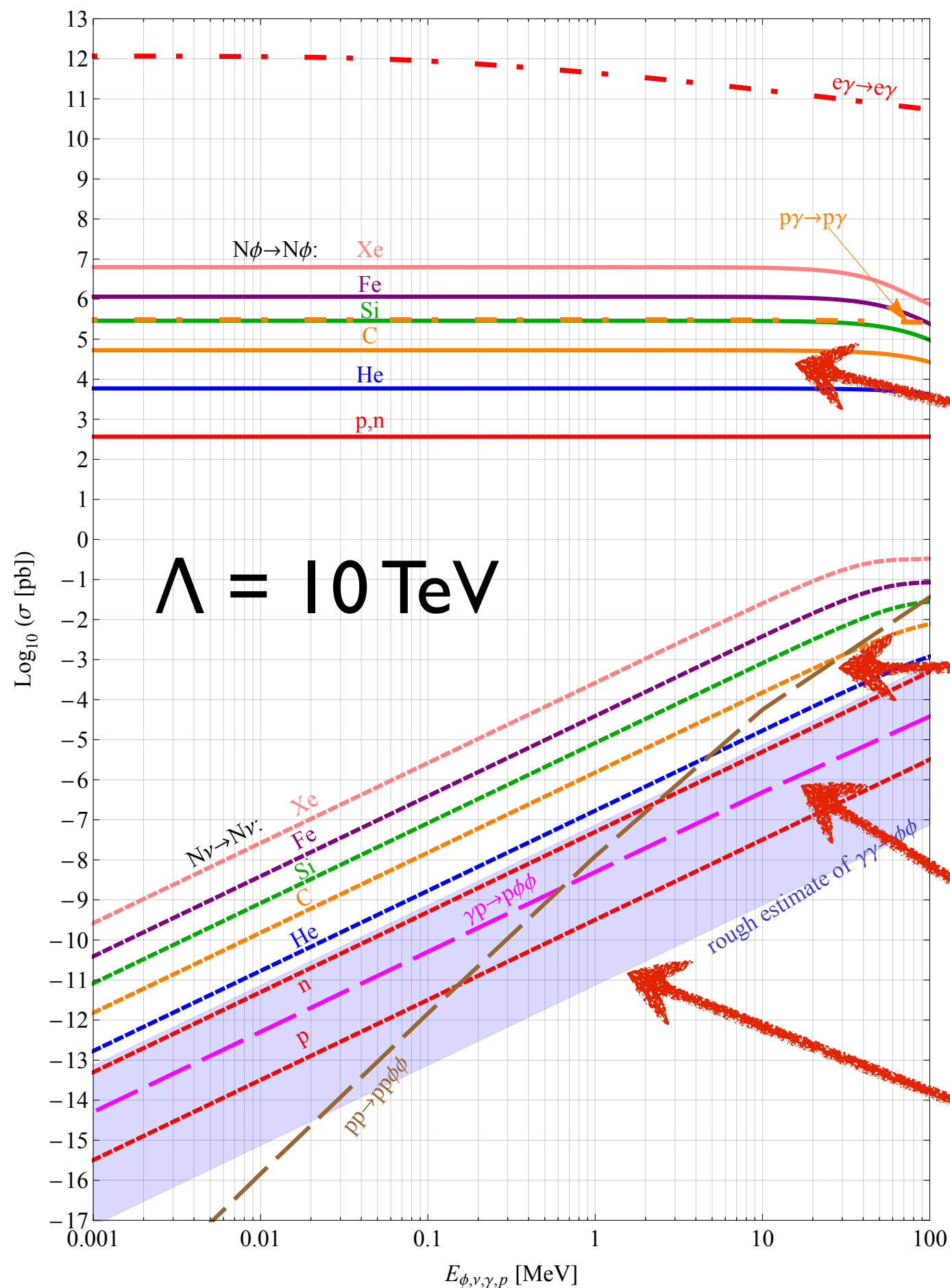
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- If we know the radial profiles of temperature and composition we can find the total loss rate (assuming  $\phi$  does not significantly alter the profiles).
- In the absence of significant  $\phi$ -matter interactions, the equilibrium total  $\phi$  loss rate is given by



**This allows us to compute the energy lost due to  $\phi$  emission.**

Compute  $\phi$  low-energy scattering and production cross sections analytically and in MadGraph.



$$\frac{\bar{q}q\phi\phi^*}{\Lambda}$$

$$\sigma_{\gamma\gamma \rightarrow \phi\phi} \sim \frac{1}{16\pi} \left( \frac{\alpha}{\pi m_q} \right)^2 \left( \frac{\mathcal{B}}{\Lambda} \right)^2 E_\gamma^2$$

with  $\mathcal{B}^2 = 1 - 100$

# The Sun



- Core temperature is about  $T \sim 1 \text{ keV}$
  - The most important  $\phi$  production process is  $\gamma N \rightarrow N \phi \phi$
  - For  $\Lambda = 10 \text{ TeV}$ ,  $\phi$  decouples at  $r \sim 0.7 \times R_{\text{sun}}$  where  $T \sim 0.1 \text{ keV}$
- solar  $\phi$  luminosity  $< 1\%$  photon luminosity requires  $\Lambda > 1 \text{ TeV}$ .
- Need the “heat transfer” of  $\phi$  to be much smaller than the photon’s

$$\frac{F_{\phi}}{F_{\gamma}} \sim \frac{n_{\phi} L_{\phi}}{n_{\gamma} L_{\gamma}} \ll 1$$

$$\frac{F_{\phi}}{F_{\gamma}} \sim n_p c \sigma_{p\gamma \rightarrow p\phi\phi} t_{\gamma}^{\text{esc}} \sim 10^{-2} \left( \frac{10 \text{ TeV}}{\Lambda} \right)^2$$

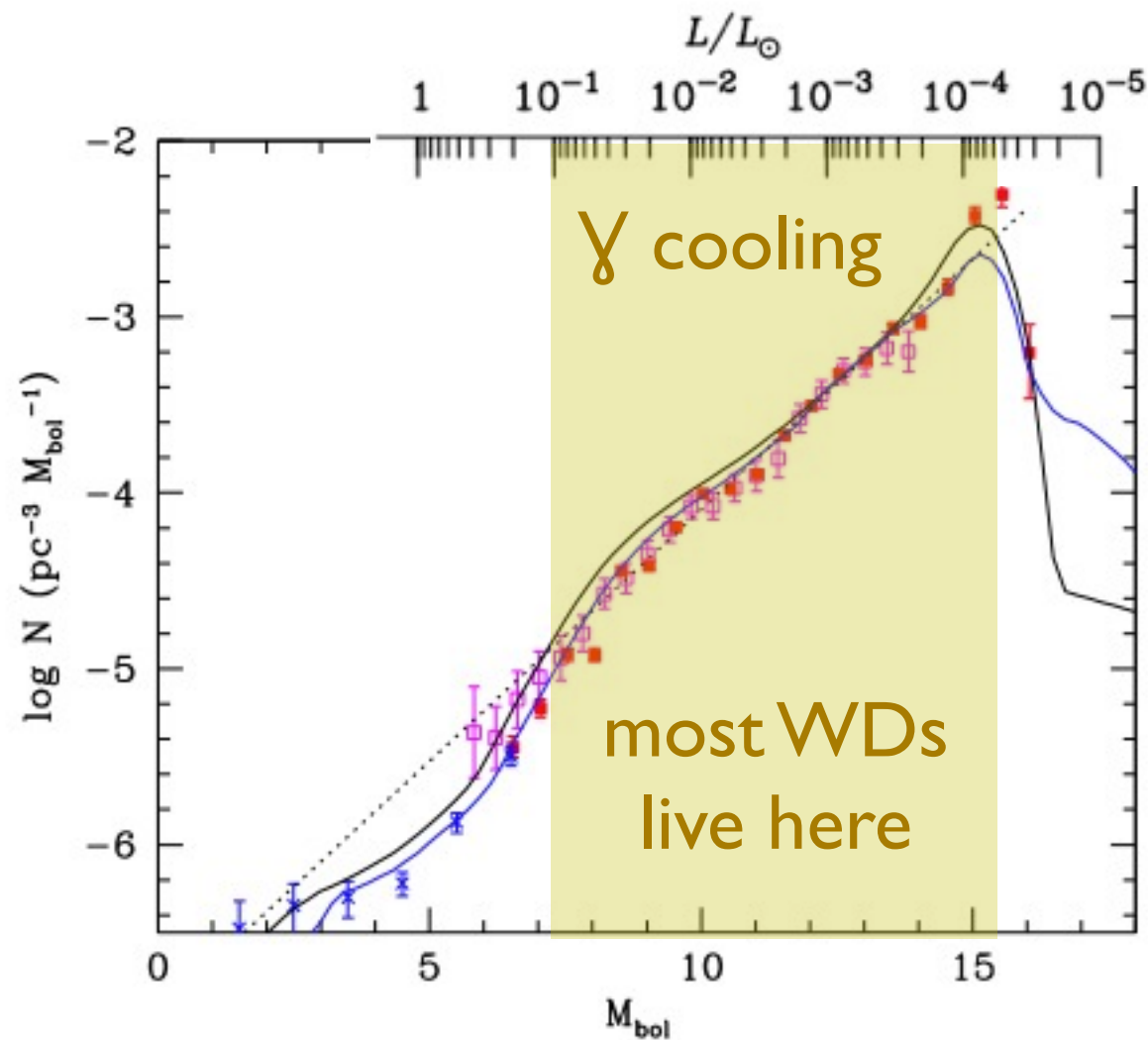
No significant constraint



# White Dwarfs



- Core temperature  $T \sim 1 - 10$  keV
- The *White Dwarf Luminosity Function* tells us how fast they cool.



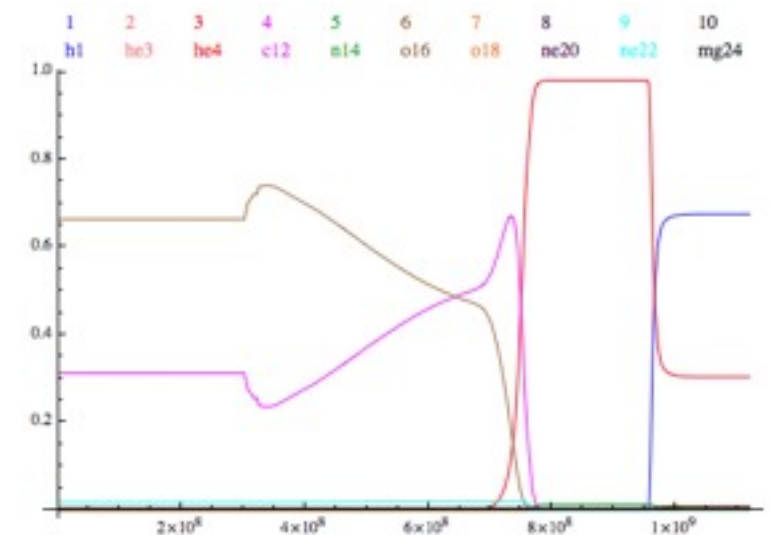
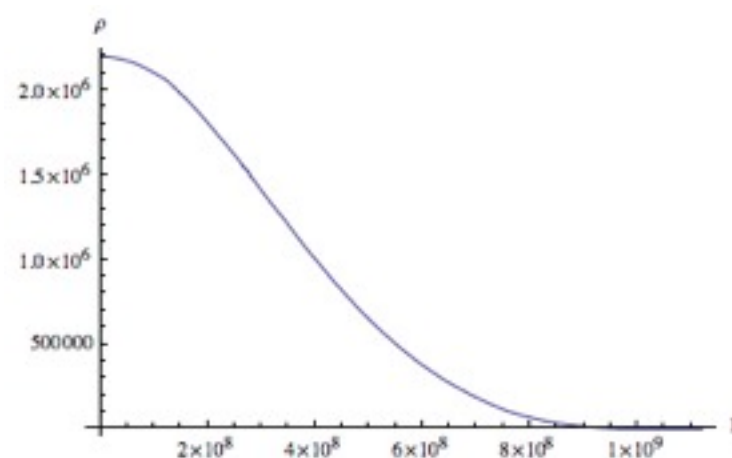
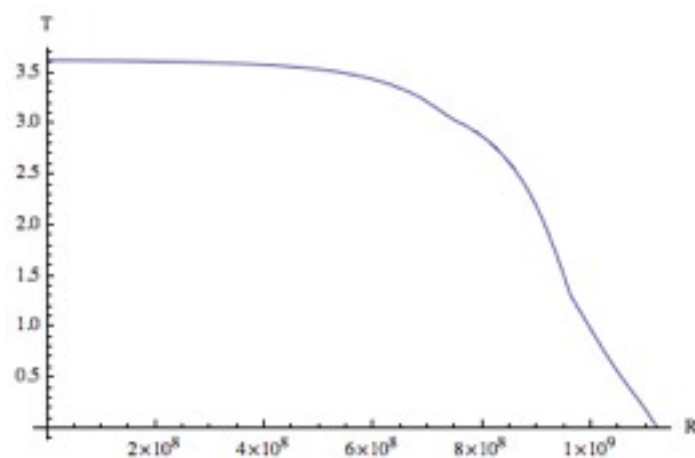
Dreiner, Fortin, Isern, Ubaldi (13')

Observational data in good agreement with standard cooling theory!

Need the scalar cooling to be much smaller than the photon cooling.

Thank you!!

Max Katz (graduate student of Michael Zingale @ SB) helped us by simulating the evolution of a sun-like star to a typical 0.5 - 0.6 solar mass WD using the MESA stellar evolution code (stellar astrophysics “gold standard”).

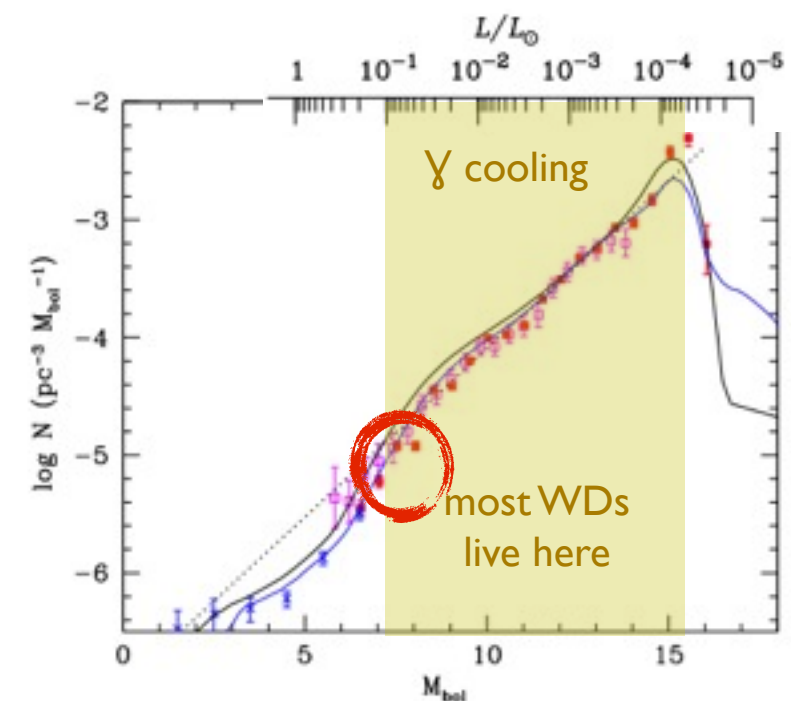


When our test dwarf has 0.1 x solar luminosity (very  $\phi$  power output is < 10% total WD luminosity if

$$\Lambda > 20 \text{ TeV}$$

$$\frac{\bar{q}q\phi\phi^*}{\Lambda}$$

( $\phi$  emission even less important at lower core temperature)



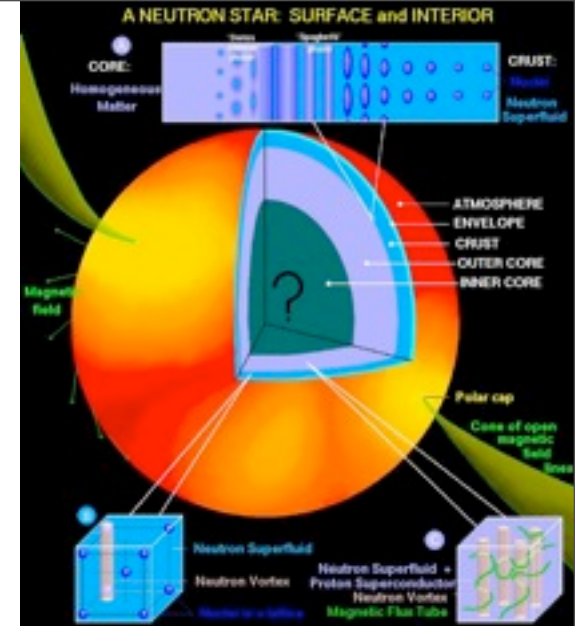
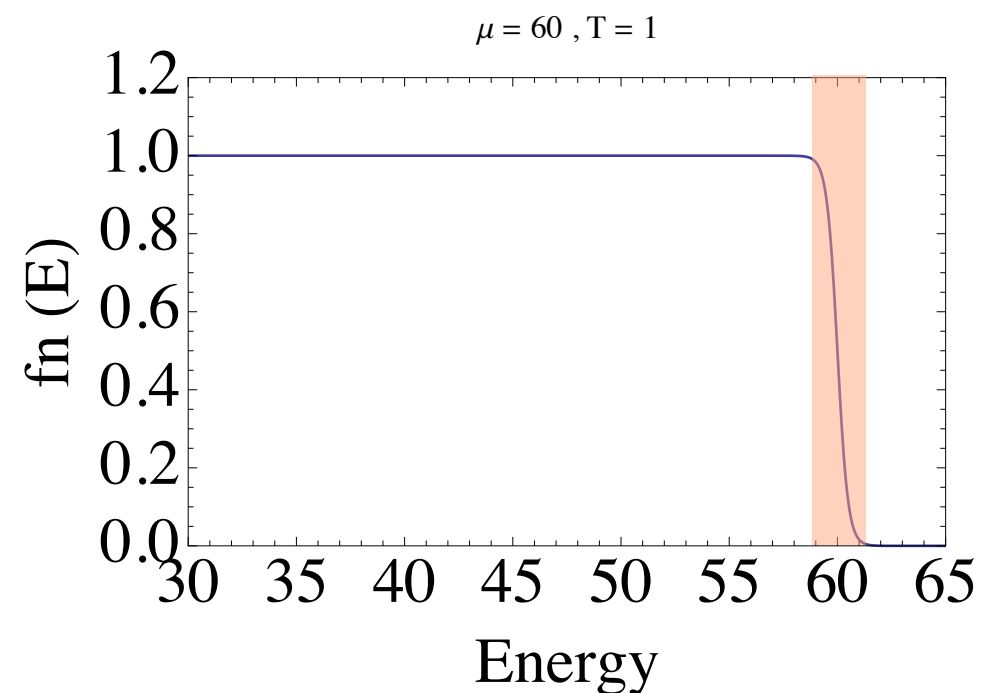
# Neutron Stars

Lots of  $\phi$  production in neutron star core via



The scattering only happens around the Fermi surface of neutrons

$$f_n(E) = \frac{1}{1 + \exp(\frac{E - \mu}{T})}$$



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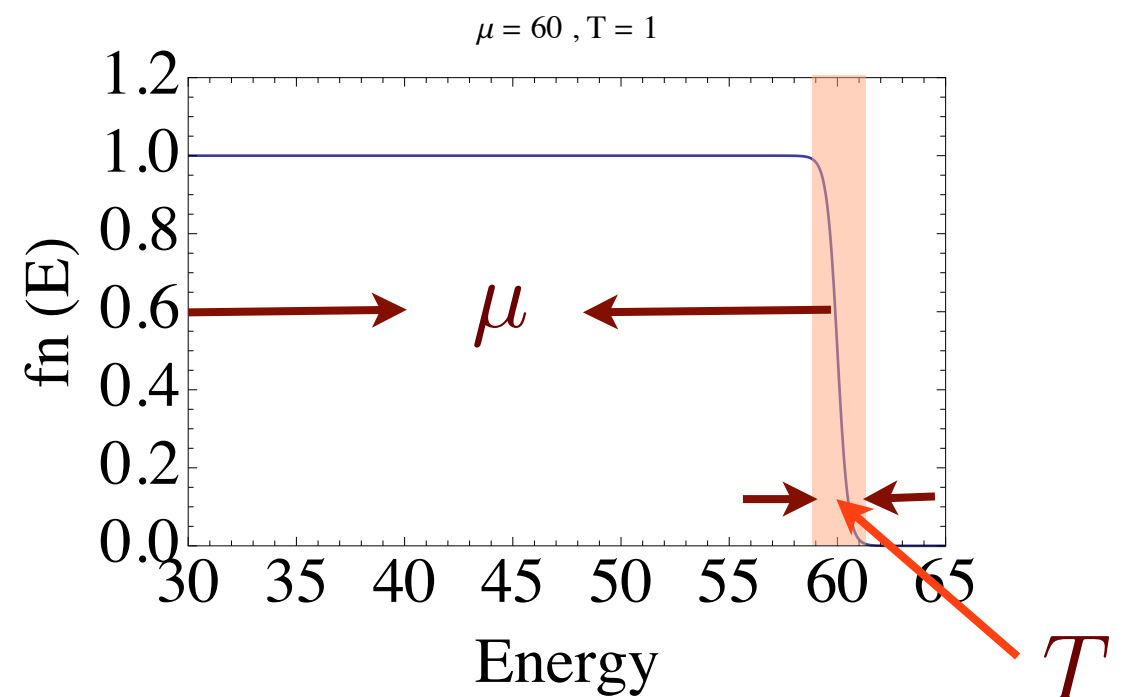
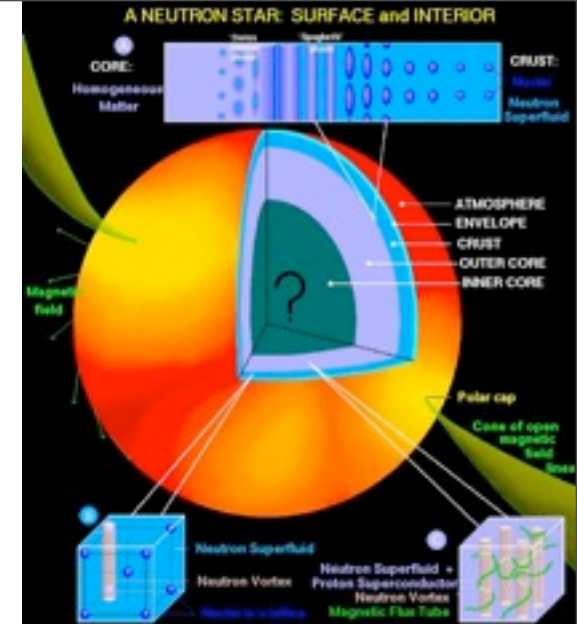
The scattering only happens around the Fermi surface of neutrons

$$f_n(E) = \frac{1}{1 + \exp(\frac{E - \mu}{T})}$$

The neutrons scattering then is suppressed by a factor

$$(T/\mu)^2 \sim 10^{-6}$$

which gives a small production rate

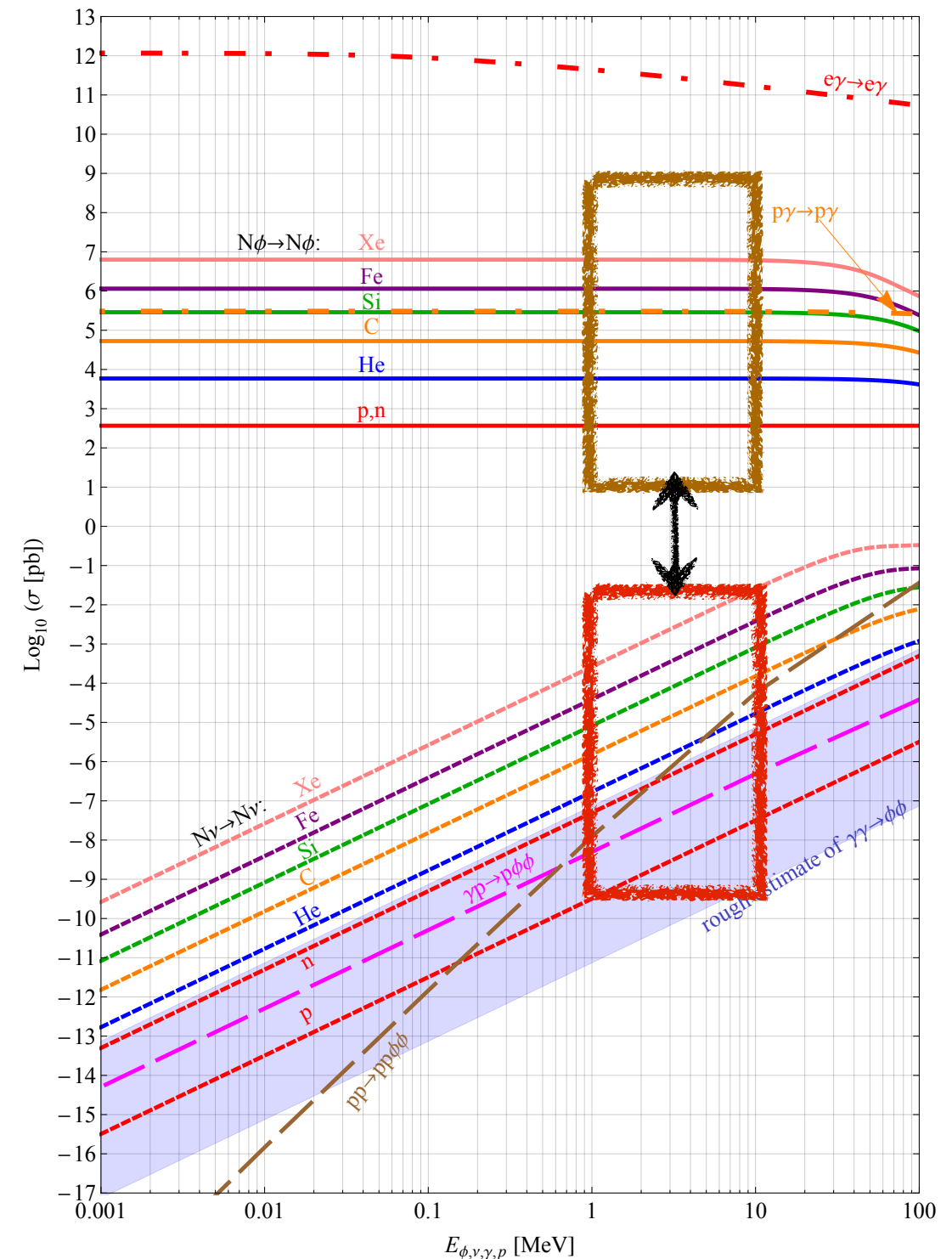


No significant constraint

## A large, bright, multi-lobed explosion or fireball, likely representing a nuclear test or a large-scale fire. The central core is intensely white and yellow, with multiple bright rays or jets of fire extending outwards in various directions. The outer edges of the fireball are a deep orange and red, suggesting intense heat. The background is dark and indistinct.

The free streaming length  $L_\phi \ll L_\nu$   
 $\phi$  then is trapped inside SN and gives no  
 significant cooling comparing to neutrinos

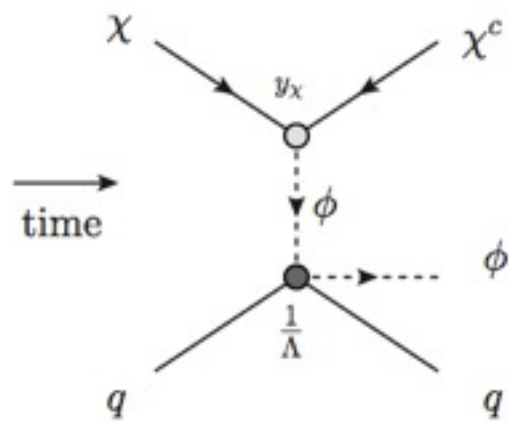
Gives an upper bound



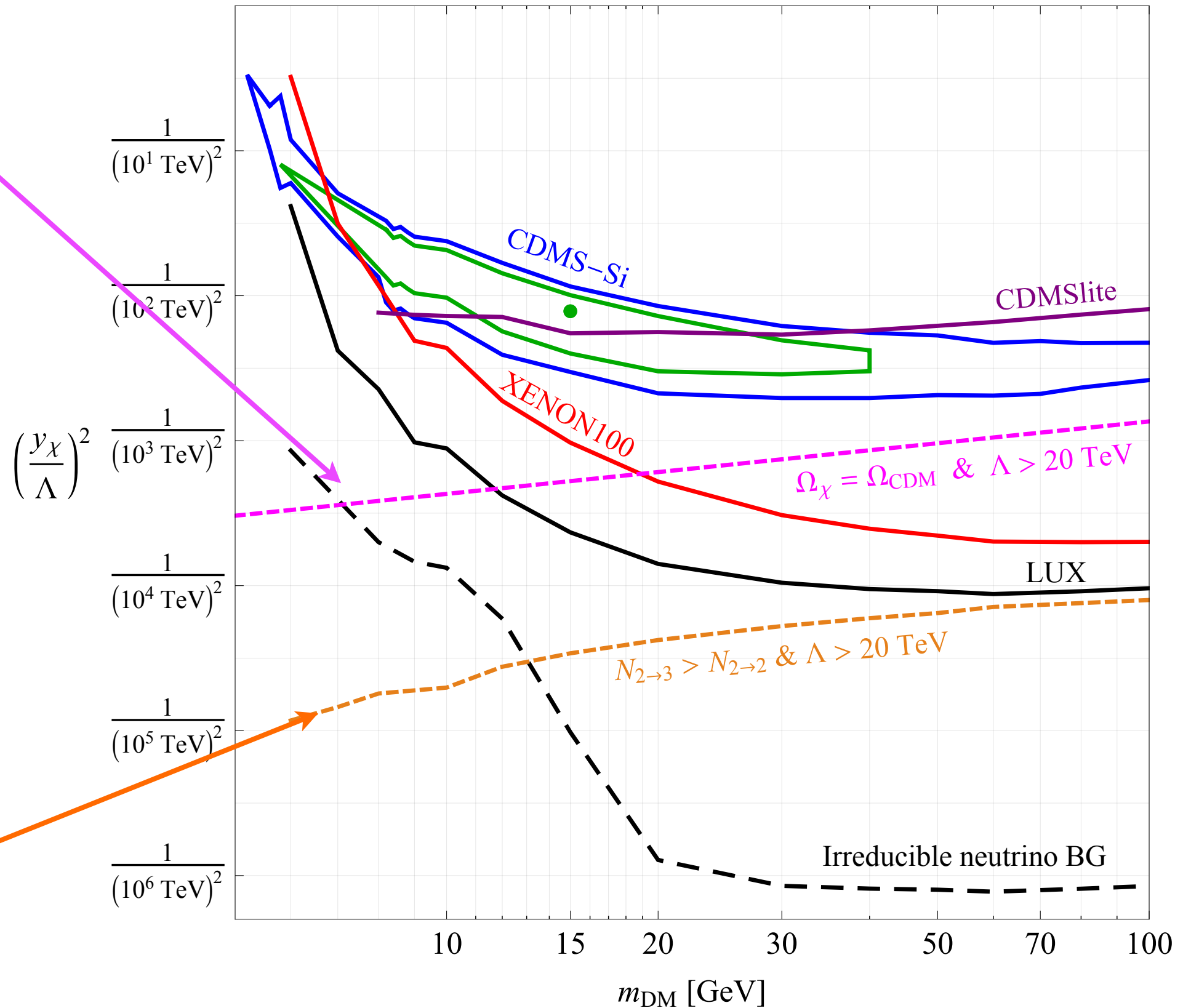


# Bound on the dmDM model

$\Lambda > 20 \text{ TeV}$   
and  
 $y_\chi$  correct value  
for DM relic  
density



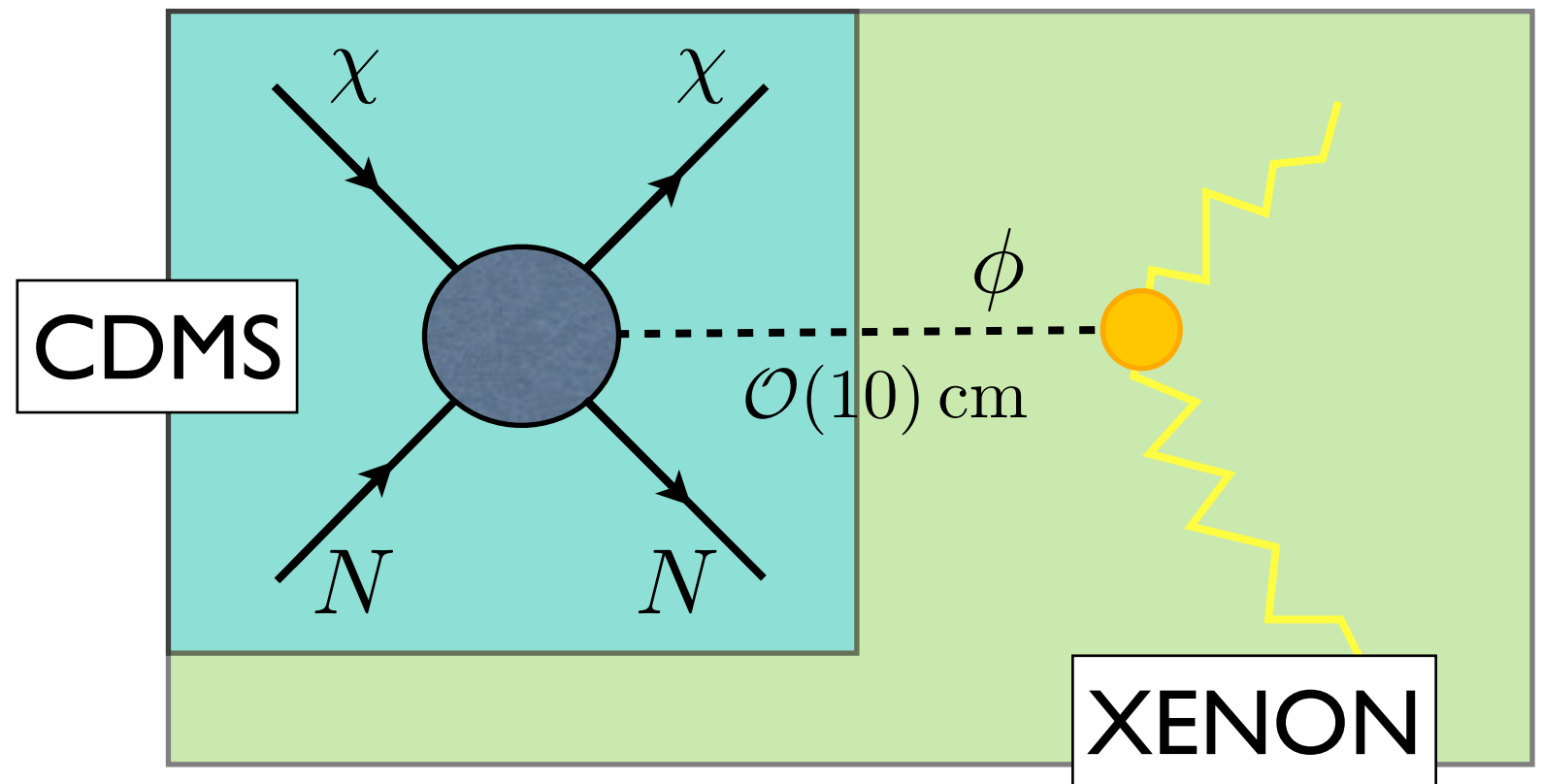
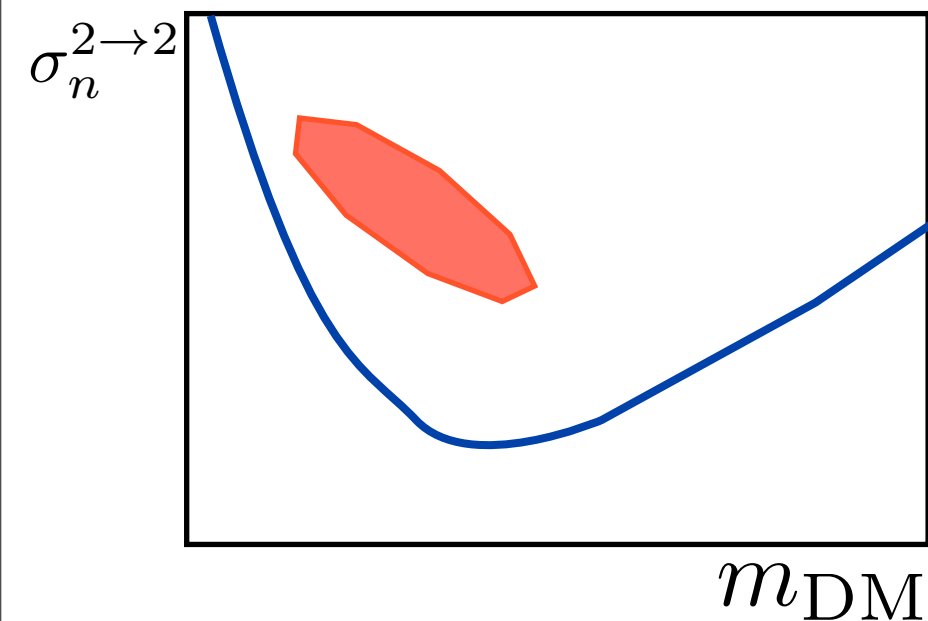
$\Lambda > 20 \text{ TeV}$   
and  
 $y_\chi$  small enough  
to ensure  
subdominant  
 $2 \rightarrow 2$





# Other “possible” uses

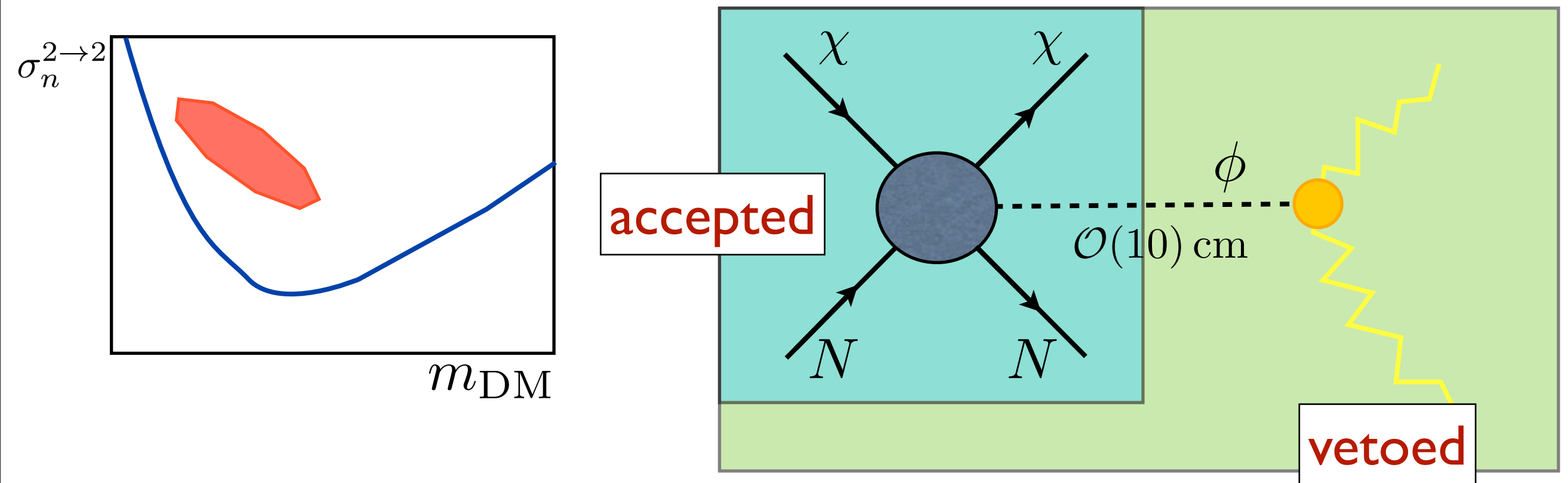
For reconciling CDMS-Si and LUX



- if this is the case, having a larger detector will not help!
- the  $\phi F_{\mu\nu} \tilde{F}^{\mu\nu} / \Lambda$  coupling needs to be large, with  $\Lambda < \text{GeV}$  unless the DM velocity is large ( $\sim 0.01$ ) so the  $\Lambda$  can be of TeV scale

# Other “possible” uses

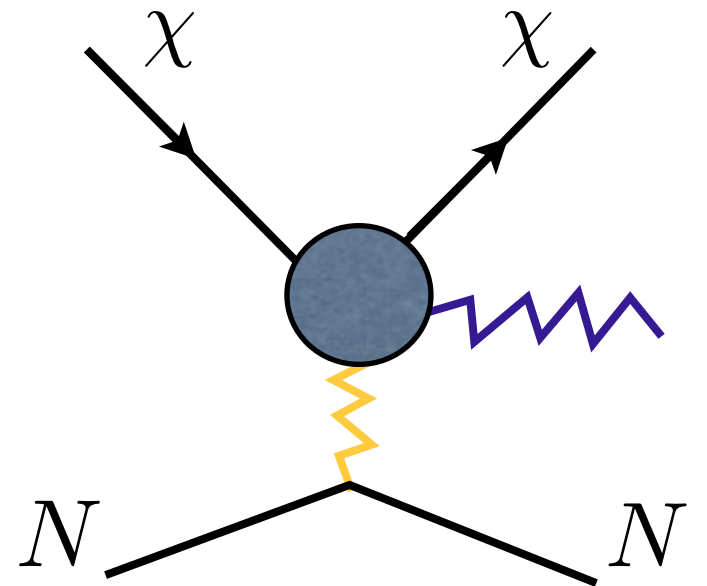
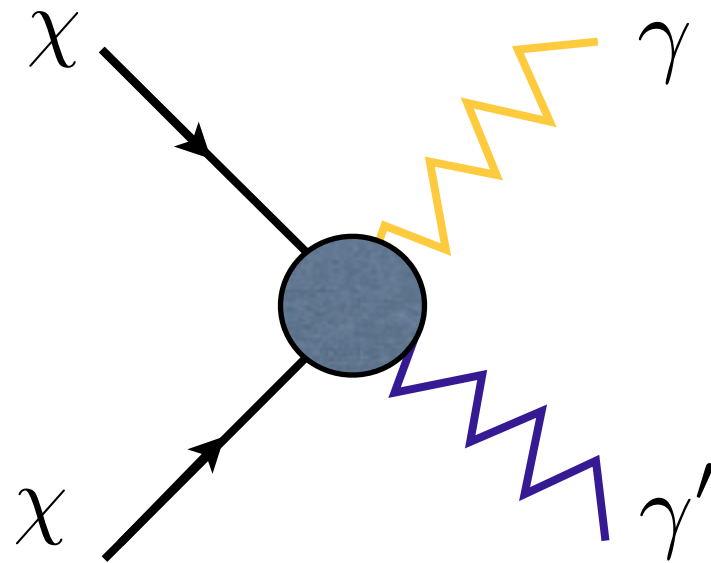
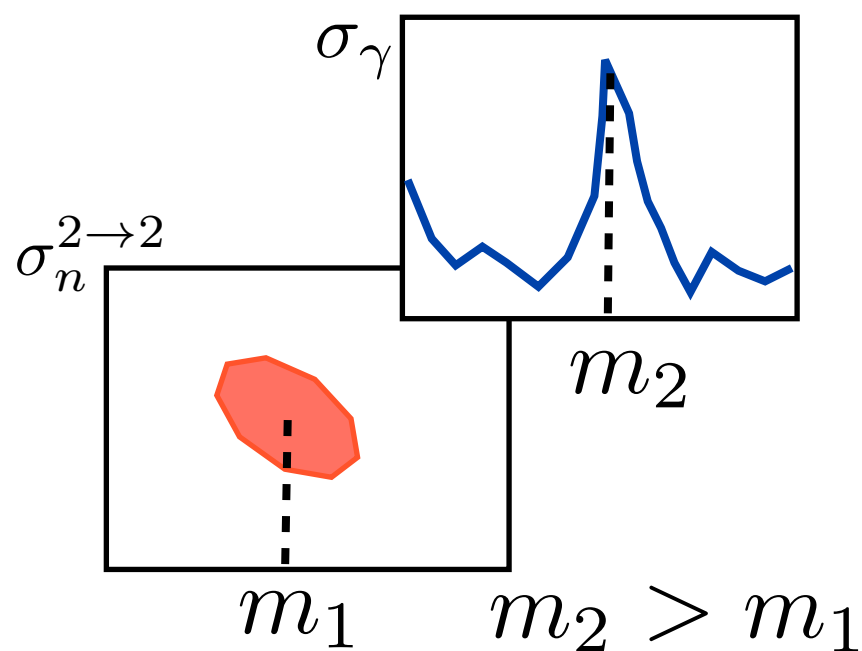
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# Other “possible” uses

For different masses from the direct/indirect detections



- DM looks lighter in a direct detection when being fitted as 2to2
- v-suppression from derivative couplings makes  $\sigma_n$  too small 😞

# Conclusion

dmDM is the first DM model featuring  $2 \rightarrow 3$  direct detection, and hence adds new kinematics to model builder's tool box.

Heavy DM candidates fake different light WIMPs at different detectors. New searching strategies will be necessary.

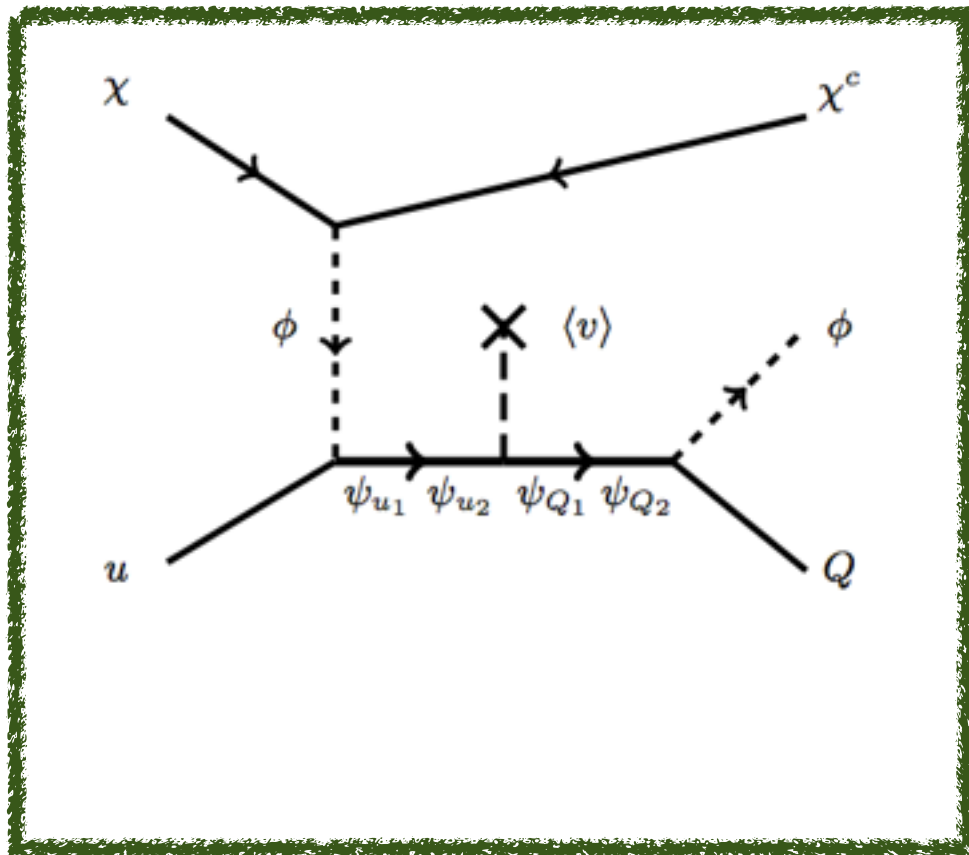
Cosmo + Astro sets significant constraints, but large regions of detectable parameter space remain. The bound can be relaxed by the heavy<sup>light</sup> setup.

Many possible applications of the dmDM model can be used for direct detections

# Backup

# A less constrained model

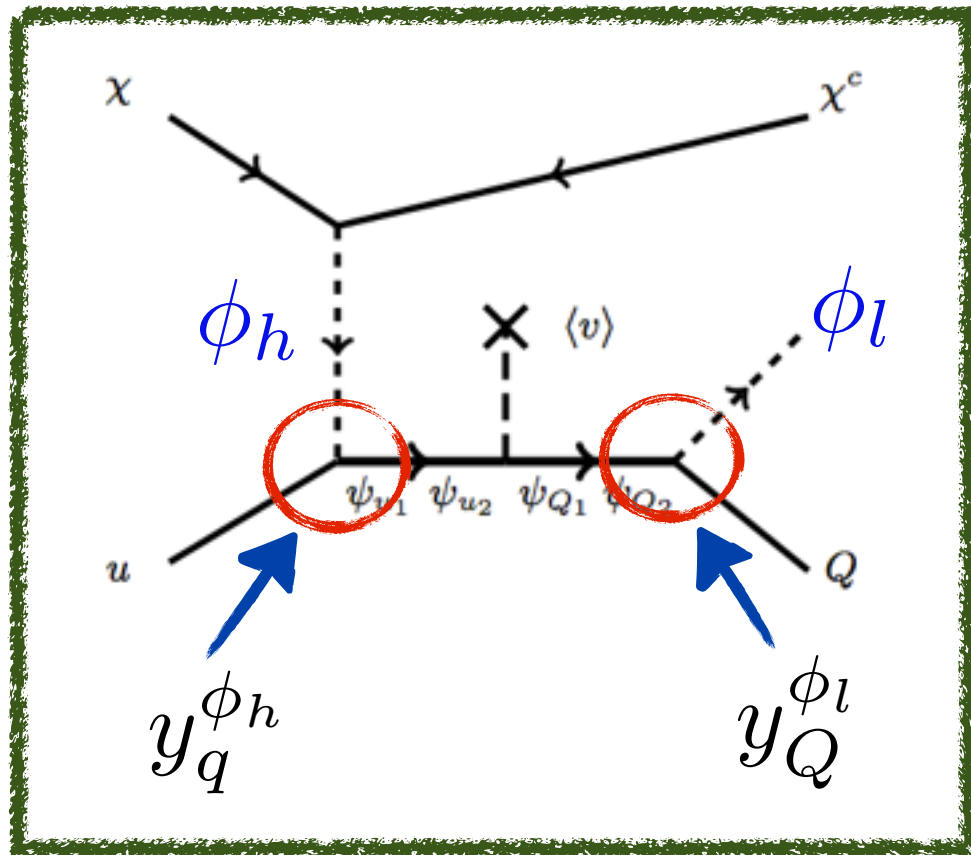
So far we only consider the simplest case with a single scalar





# A less constrained model

So far we only consider the simplest case with a single scalar

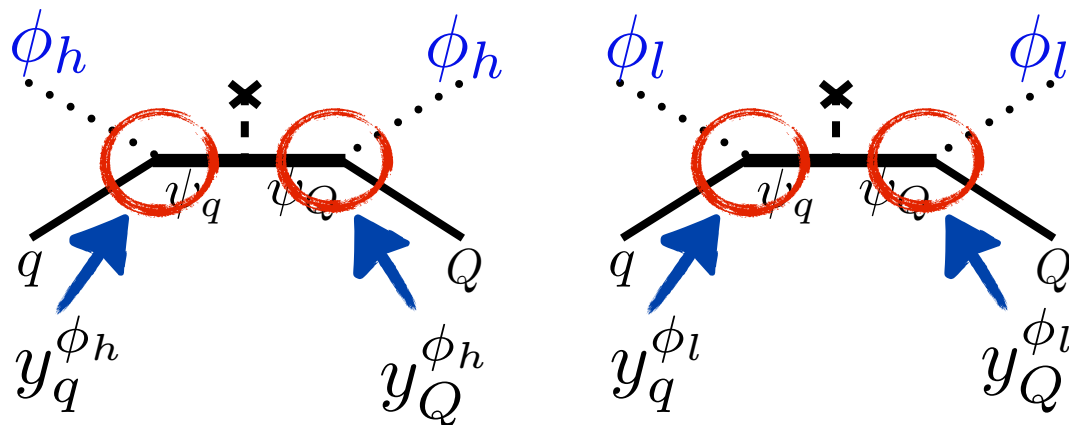


**heavy**light model with

$$m_{\phi_h} \simeq 1 \text{ MeV}, \quad m_{\phi_l} < 1 \text{ keV} \quad y_q^{\phi_l} < 0.1$$

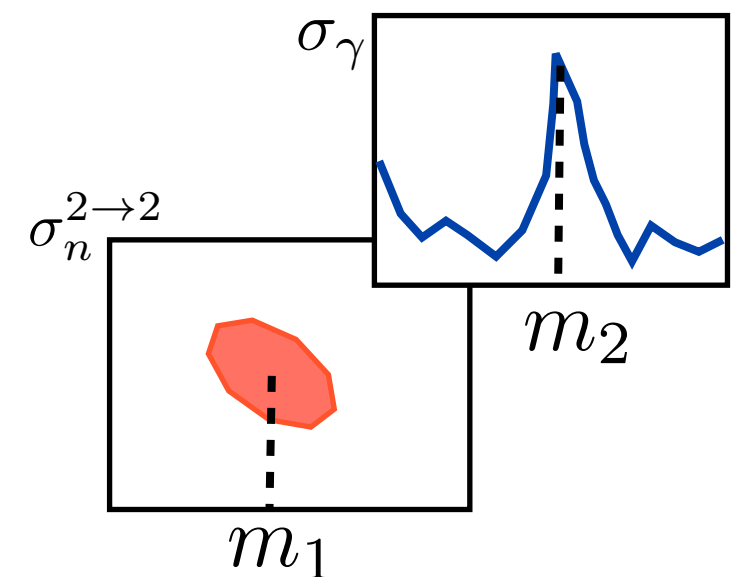
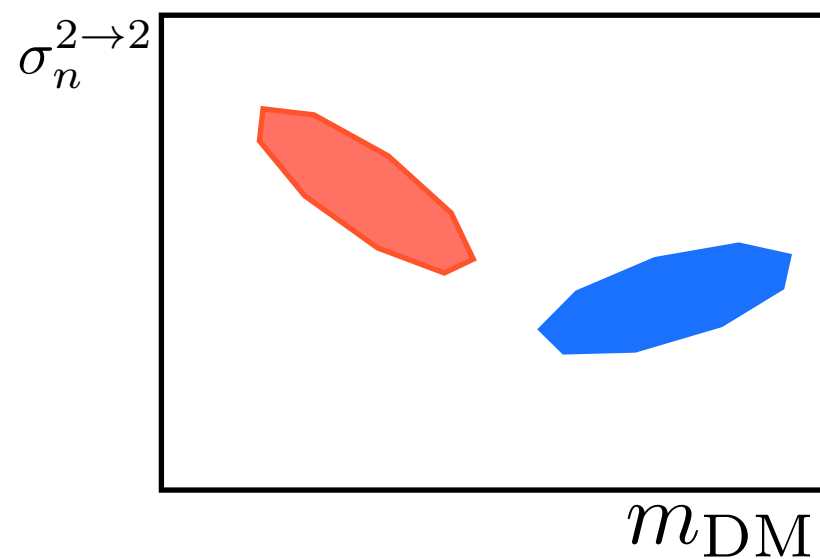
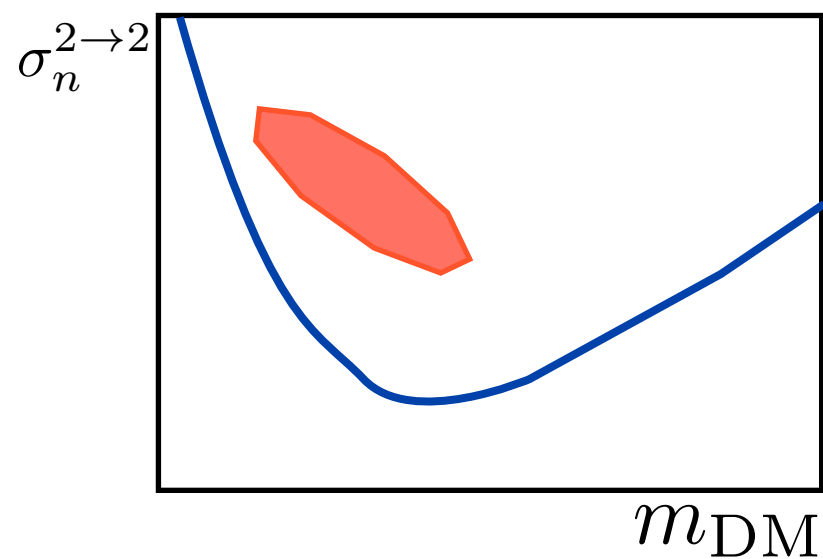
to avoid the sizable stellar production of  $\phi$

Moreover, if  $y_{\chi\phi_l}, y_Q^{\phi_h} < 10^{-3}$ ,  
the loop-induced 2 to 2 process will be  $< 10\%$   
of the 2 to 3 while keeping the  $\sigma_{2 \rightarrow 3}$  large



$\phi_h$  can decay promptly through a  $\phi_h \phi_l^3$   
coupling (assuming the Z4 case)

# Other possible use of 2to3



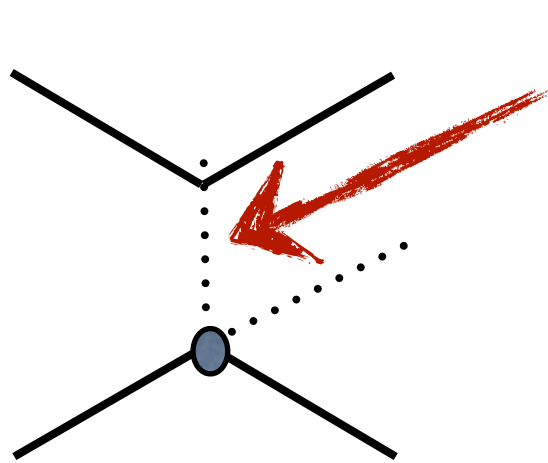
# $E, |\vec{p}|$ in a non-relativistic scattering

the DM and nucleus have  $v \ll 1 \Rightarrow E_k = \frac{1}{2} m v^2 \ll |\vec{p}| = m v$

however, the relativistic scalar has  $E^\phi \simeq |\vec{p}_\phi|$ , this requires

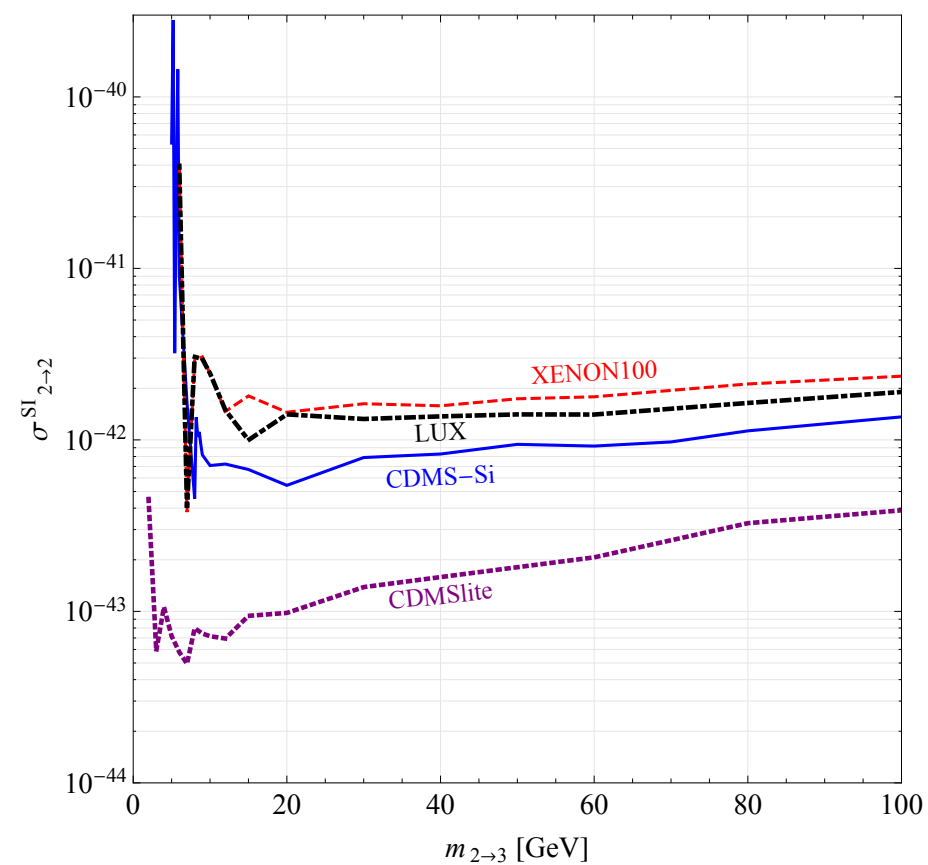
$$|\vec{p}_\phi| \simeq E^\phi < E_k^\chi \ll |\vec{p}_{\chi, N}|$$

$\phi$  carries away sizable energy but not much momentum!

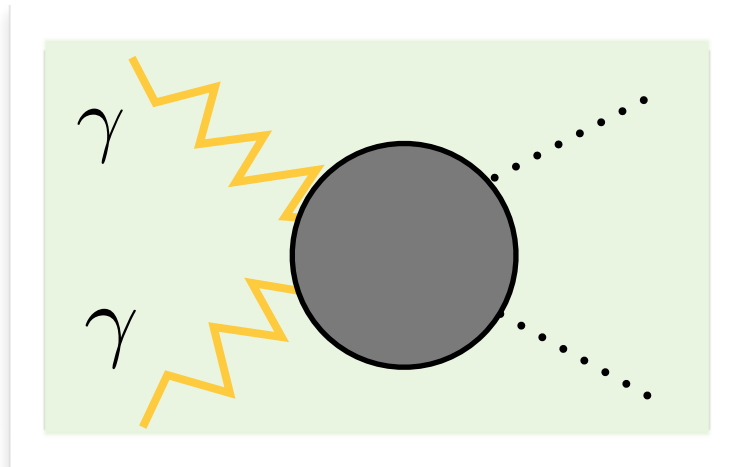


$$\begin{aligned} (\Delta p_N + p_\phi)^{-4} &\simeq (\Delta p_N^2 + 2p_\phi \cdot \Delta p_N)^{-2} \\ &\simeq (|\vec{p}_N|^2 + 2|\vec{p}_\phi||\vec{p}_N|)^{-2} \\ &\simeq (2m_N E_R)^{-2} \end{aligned}$$

# Interaction strength



# Cosmological Constraints : $N_{\text{eff}}$



The cross section is hard to estimate...  
assuming a quark loop with constituent quark mass, multiplied by a range of the form factor

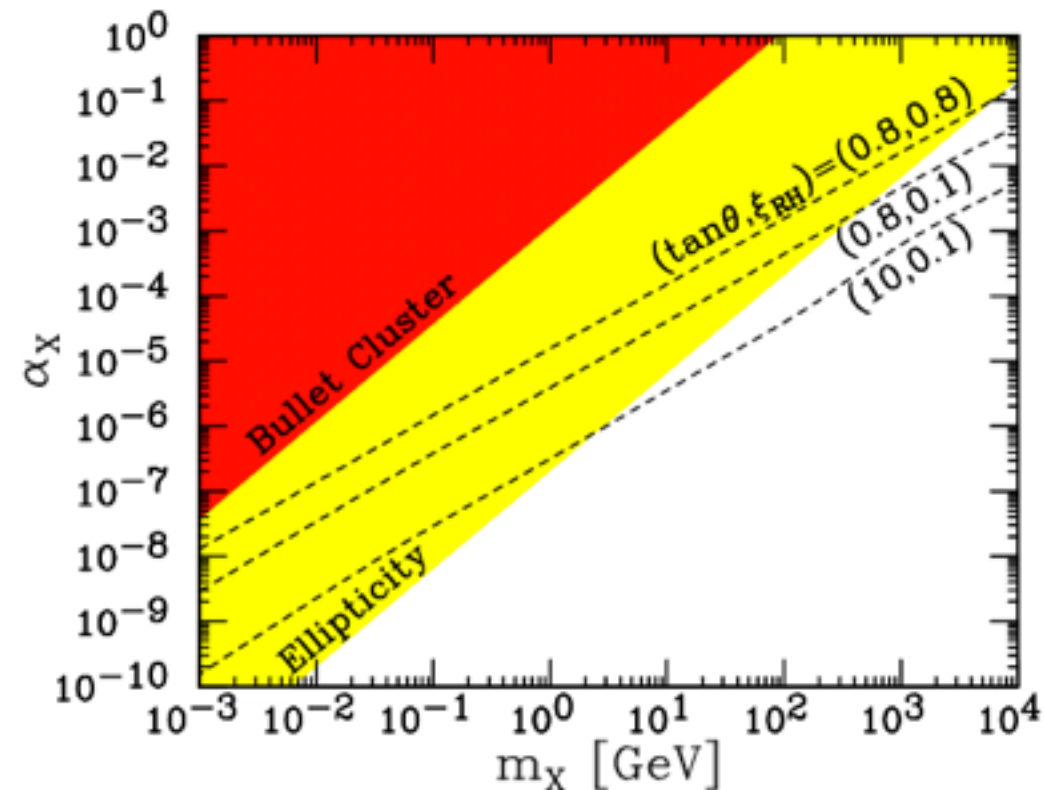
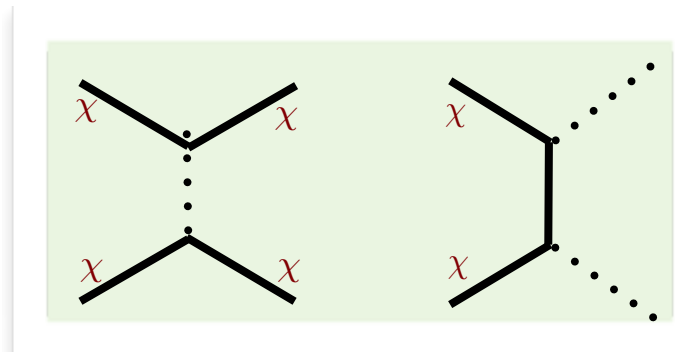
$$\sigma_{\gamma\gamma \rightarrow \phi\phi} \sim \frac{1}{16\pi} \left( \frac{\alpha}{\pi m_q} \right)^2 \left( \frac{\mathcal{B}}{\Lambda} \right)^2 E_\gamma^2 \quad \mathcal{B}^2 = 1 - 100$$

$\phi$  decoupled from thermal bath at  $T_\phi^{\text{freeze}} > 10 \text{ MeV} \left( \frac{\Lambda}{10 \text{ TeV}} \right)^{2/3}$

If the decoupling happens just before the BBN,  $N_{\text{eff}}$  has a  $2\sigma$  deviation from the current measurement  $N_{\text{eff}} = 3.36_{-0.64}^{+0.68} \text{ (95 \% CL)}_{\text{Planck+WMAP+HighL}}$

This can be relaxed when having  $\phi$  as a real scalar charged under a  $Z_4$  symmetry  $\phi \rightarrow -\phi, \chi \rightarrow e^{i\pi/2} \chi$

# Constraints on the dark coupling



Jonathan L. Feng, Manoj Kaplinghat, Huitzu Tu, and Hai-Bo Yu (09)

- Bullet cluster bound requires  $y_{\chi\phi} < 1$  when having a single light mediator and 10-100 GeV DM.
- DM being a thermal relic requires  $y_\chi \approx 2.7 \times 10^{-3} (m_\chi/\text{GeV})^{1/2}$

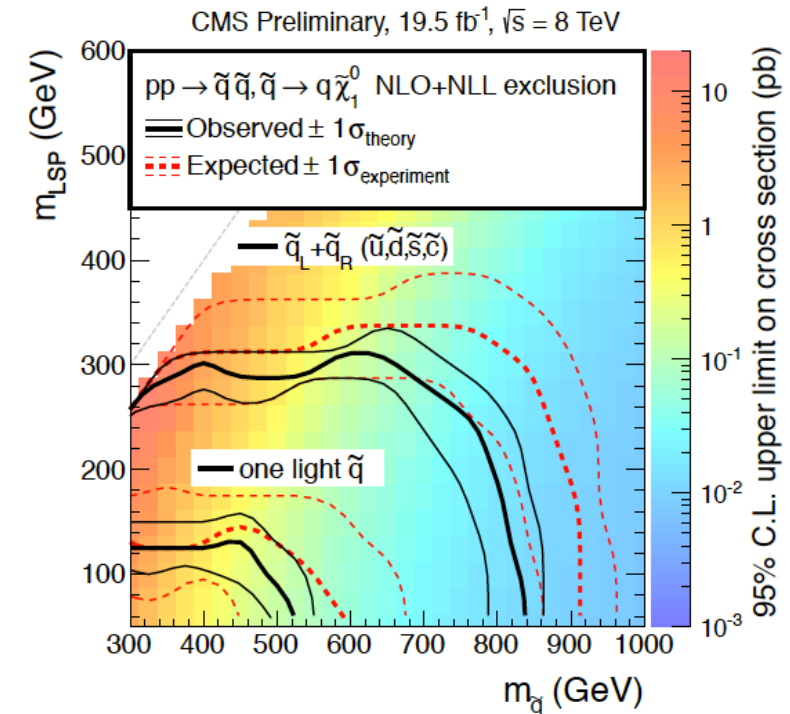


# Collider bounds : LHC

di-jet  $pp \rightarrow \psi_Q \bar{\psi}_Q \rightarrow \phi \phi^* jj$

CMS 20/fb bound on the production rate requires

$$M_Q > 1.5 \text{ TeV}$$

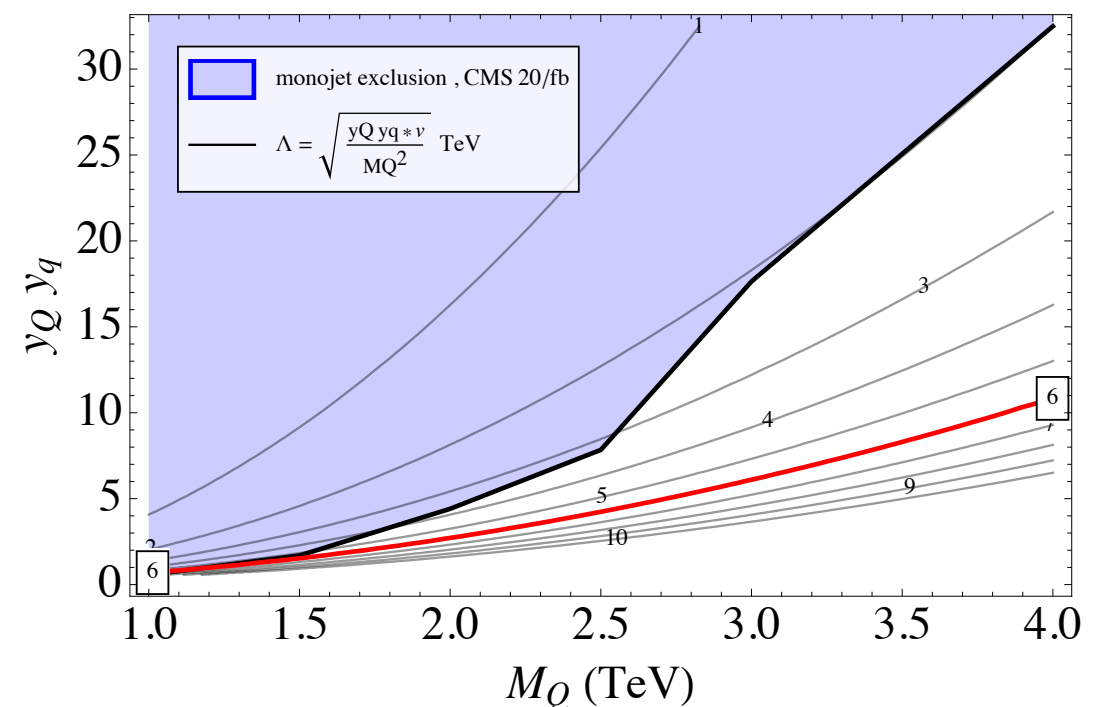


mono-jet  $pp \rightarrow q^* \rightarrow \phi \psi_{Q,q} \rightarrow \phi j$ ,  
MG5+Pythia+PGS

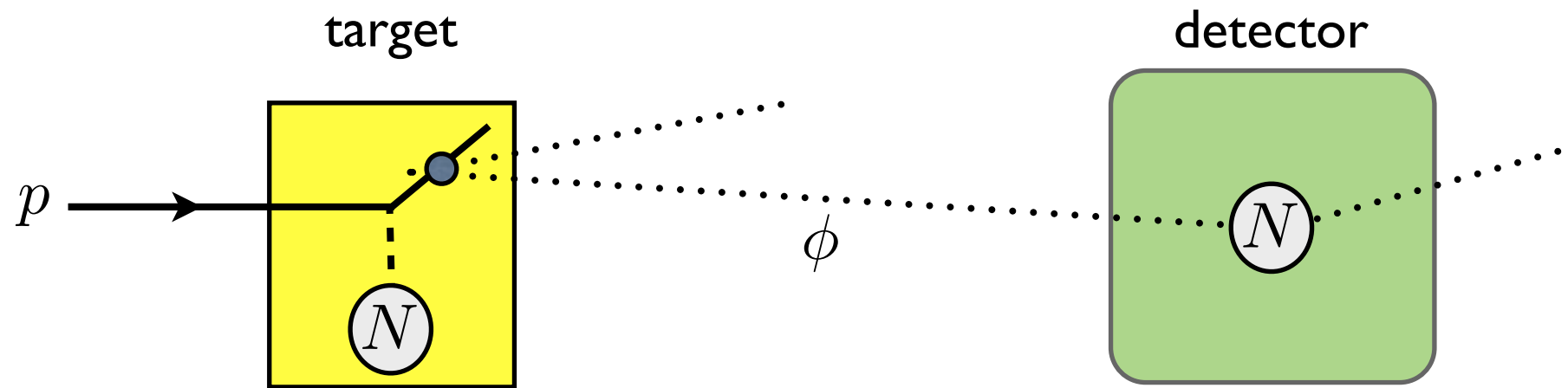
$pp \rightarrow \phi \phi + \text{ISR}$

CMS 20/fb bound requires  $\Lambda > 6 \text{ TeV}$   
when  $M_Q \simeq 1.5 \text{ TeV}$

No significant bound



# Collider bounds : fixed target



	$E_p$	$N_{\text{POT}}$	detector distance	detector dimensions
MINOS [64, 65]	120 GeV	$10.7 \cdot 10^{20}(\nu), 3.36 \cdot 10^{20}(\bar{\nu})$	$\sim 100 \text{ m}, 735 \text{ km}$	$\sim 10\text{m}$
T2K [66-68]	30 GeV	$6.63 \cdot 10^{20}$	280m (INGRID in ND280) 295 km (Super-Kameiokande)	$\sim 10 \text{ m}$ $\sim 40 \text{ m}$
MiniBooNE [69]	8.9 GeV	$6.5 \cdot 10^{20}(\nu), 11.3 \cdot 10^{20}(\bar{\nu})$	541 m	$\sim 10 \text{ m}$
LSND [70]	800 MeV	$1.8 \cdot 10^{23}$	30 m	0.3 m
$\phi$ production rate			geometrical suppression	

even with detection efficiency = 1  
 $E_p = 120 \text{ GeV}$

$$\frac{N_{\phi}^{\text{detected}}}{10^{-6}} \sim \left( \frac{N_{\text{POT}}}{10^{21}} \right) \left( \frac{10 \text{ TeV}}{\Lambda} \right)^4 \left( \frac{L_{\text{target}} L_{\text{detector}}}{\text{meter}^2} \right)$$

number of the observed events  $\ll 1$

**No significant bound**

# Collider bounds : kaon decay

$\frac{\phi^* \phi \bar{Q} q}{\Lambda}$  can generate a tree-level decay of scalar mesons, or loop-induced decay through a flavor changing process

$$K^+ \rightarrow \pi^+ \phi \phi^*$$

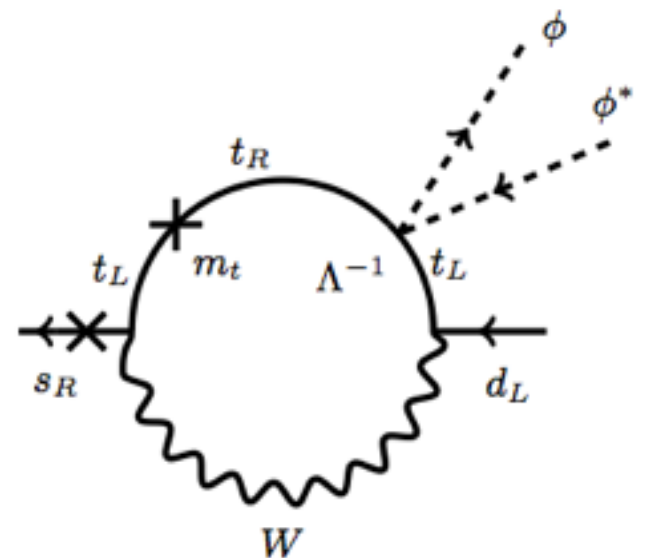
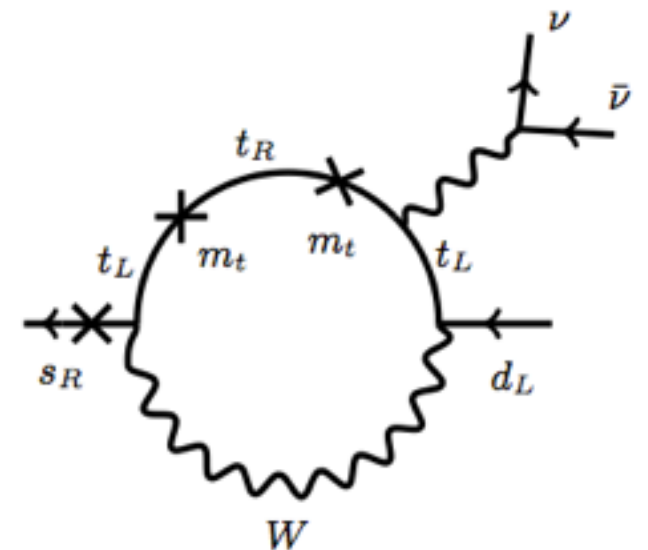
current experimental precision

$$Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{exp}} = 17.3_{-10.5}^{+11.5} \cdot 10^{-11}$$

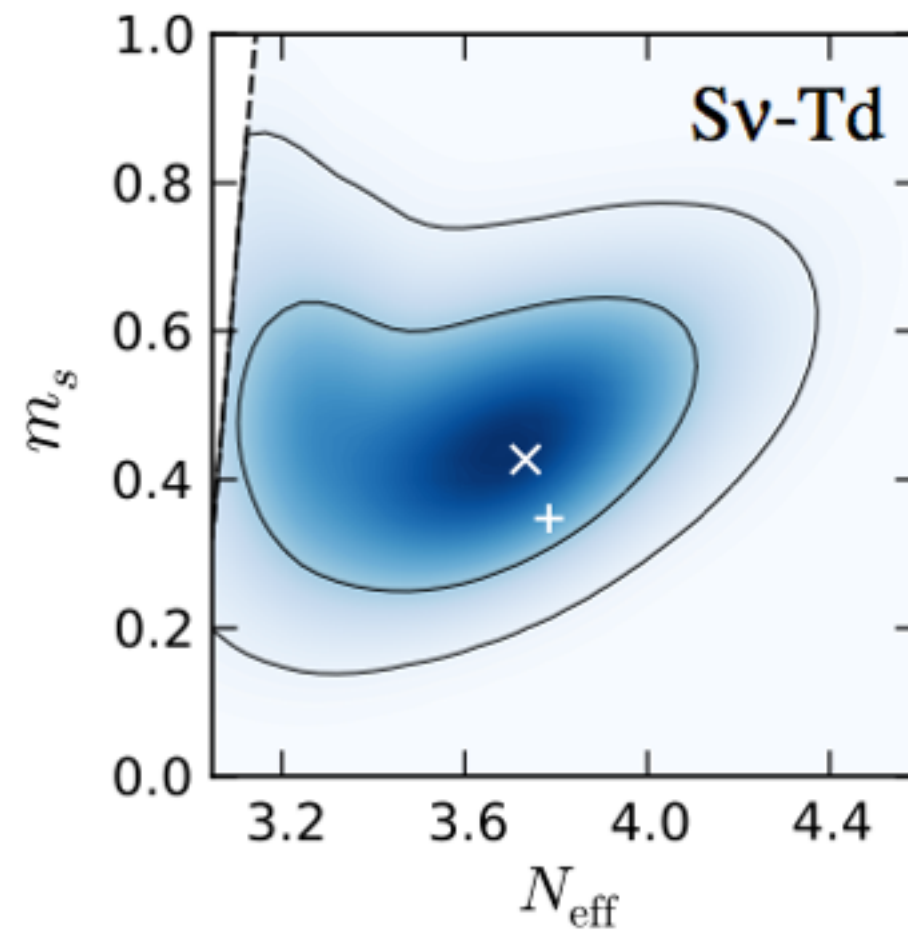
$$Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}} = (8.5 \pm 0.7) \cdot 10^{-11}$$

$$\frac{|\mathcal{M}_{\phi\phi}|}{|\mathcal{M}_{\text{SM}}|} \sim \frac{m_Z^2}{g_{Zq} g_{Z\nu} m_t \Lambda} = 0.03, \quad \Lambda = 10 \text{ TeV}$$

No significant bound



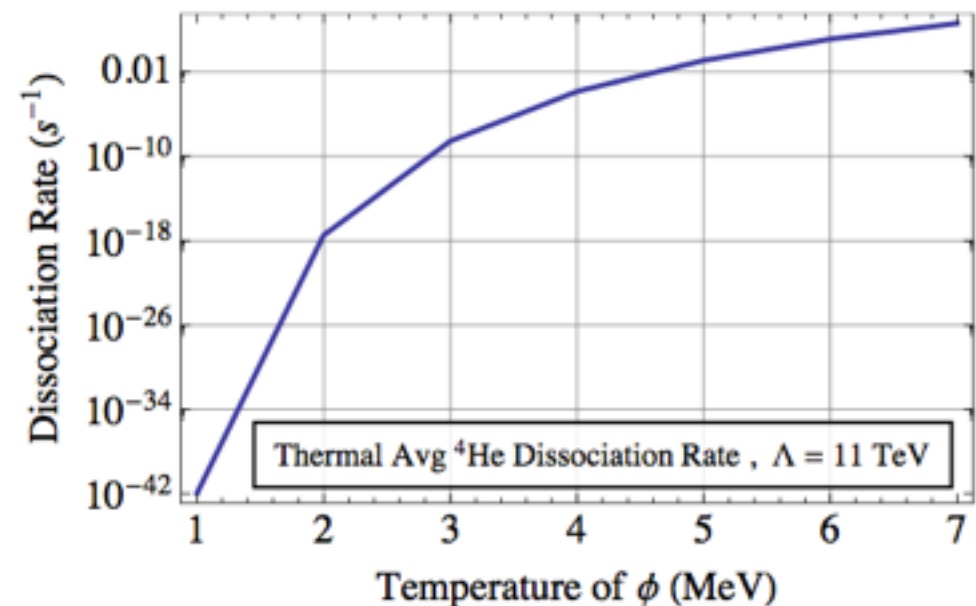
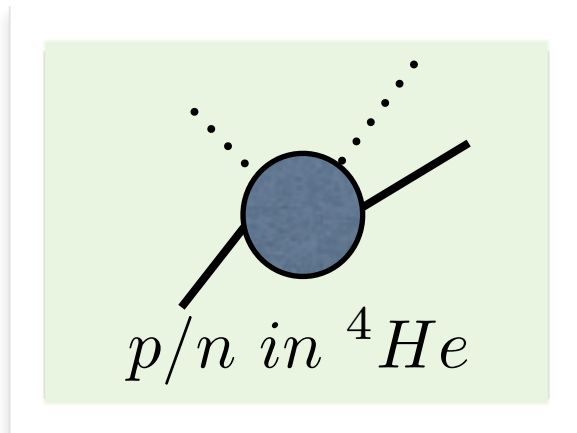
# Bound on light sterile neutrino



Planck+WMAP+H0+BAO+Xray cluster

Mark Wyman, Douglas H. Rudd, R. Ali Vanderveld, and Wayne Hu (13)

# Cosmological Constraints : $4\text{He}$



- $\phi$  can in principle dissociate a  $4\text{He}$  during the BBN time. However, the min recoil energy that a  $\phi$  needs to kick out a nucleon from  $4\text{He}$  is **7.1 MeV**, which requires  $E_\phi > 125 \text{ MeV}$  when the temperature is below **10 MeV**.  $E_R^{\text{max}} = 2 E_\phi^2 / m_{4\text{He}}$
- Calculating the dissociation rate by including the Boltzmann distribution sets a bound  **$\Lambda > 11 \text{ TeV}$**  when comparing the dissociation probability of  $4\text{He}$  to the current precision  $\frac{\delta n_{\text{He}}}{n_{\text{He}}} \simeq \frac{0.04}{0.26} = 15 \%$

$$m\phi = 0.2 \text{ KeV}$$

DOTTED = (collaboration bounds)  $\rightarrow$  (WIMP to dmDM map)

SOLID = exclusion from directly fitting dmDM to data

Green (Blue) = 68 (90) % CL CDMS–Si preferred region

Red = 90%CL upperbound from XENON100

Purple = 90%CL upperbound from CDMSlite

$$\text{Magenta} = \frac{\Lambda^{\min}}{y_{\text{relic}}}, \text{ where } \Lambda^{\min} = 100 \text{ TeV from WD}$$

