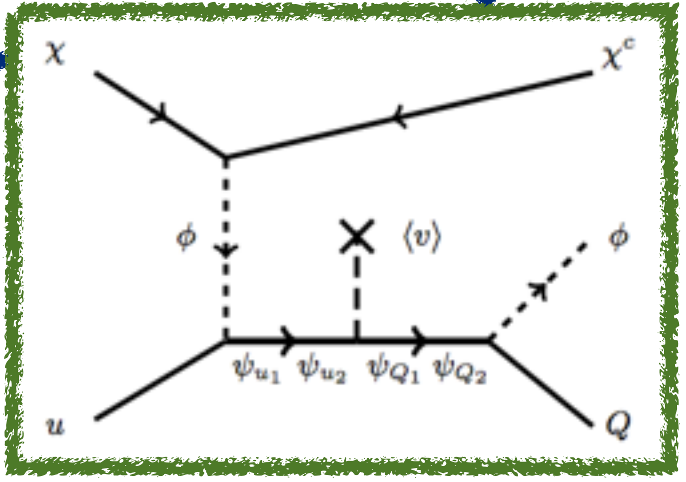
Direct Detection of the Dark Mediated DM



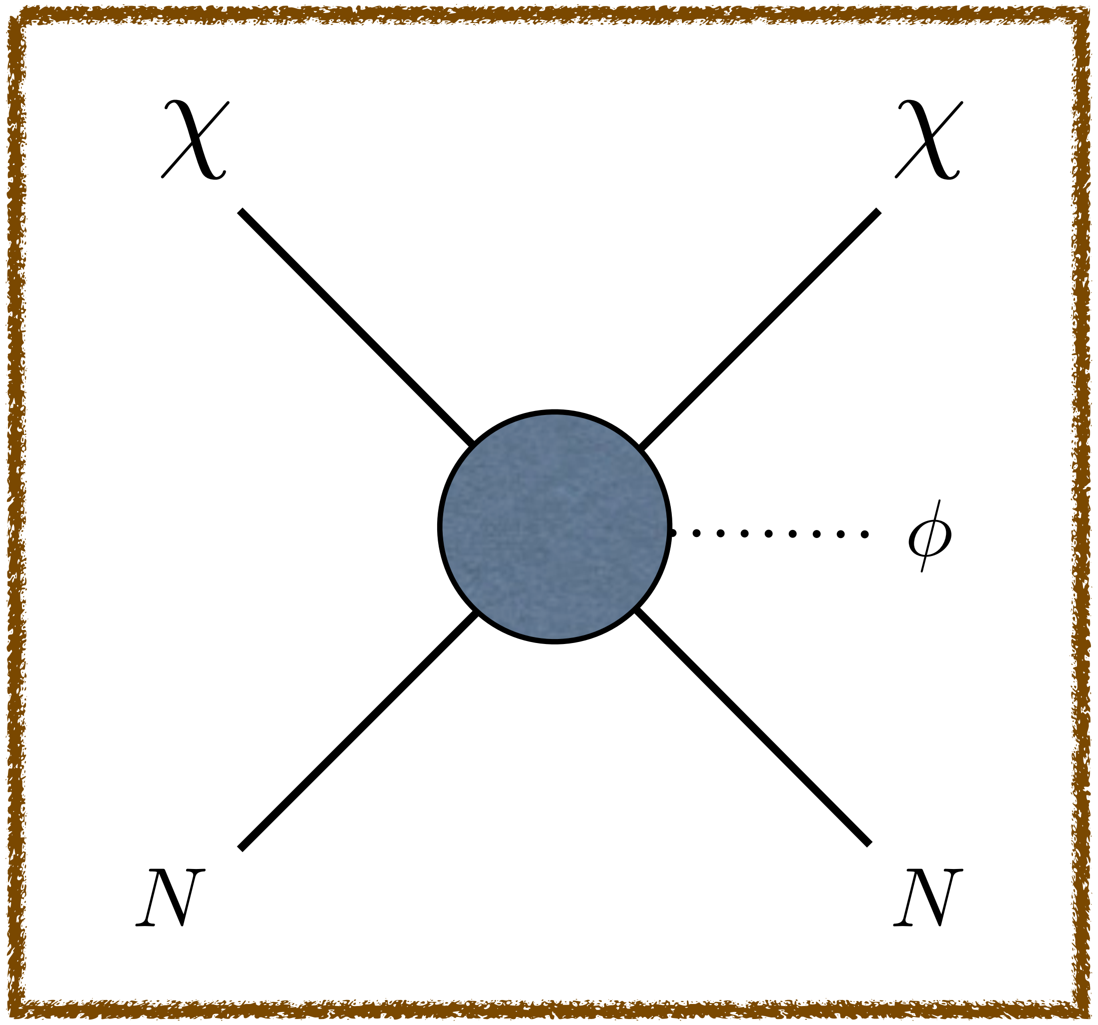
Yuhsin Tsai

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

1312.2618 and 1402.XXXX

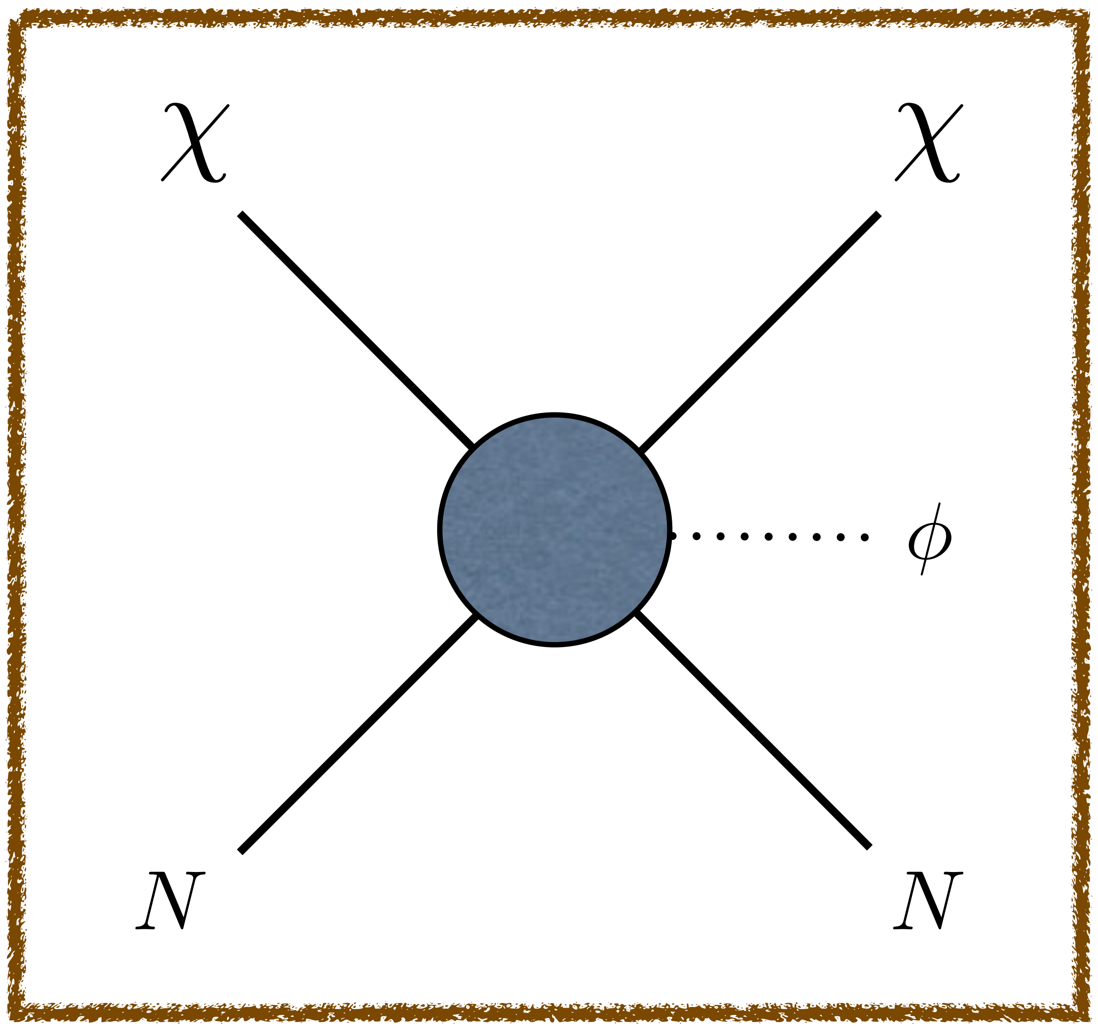
UC Davis Jan 16 2014

Main questions



How does the direct detection look like?

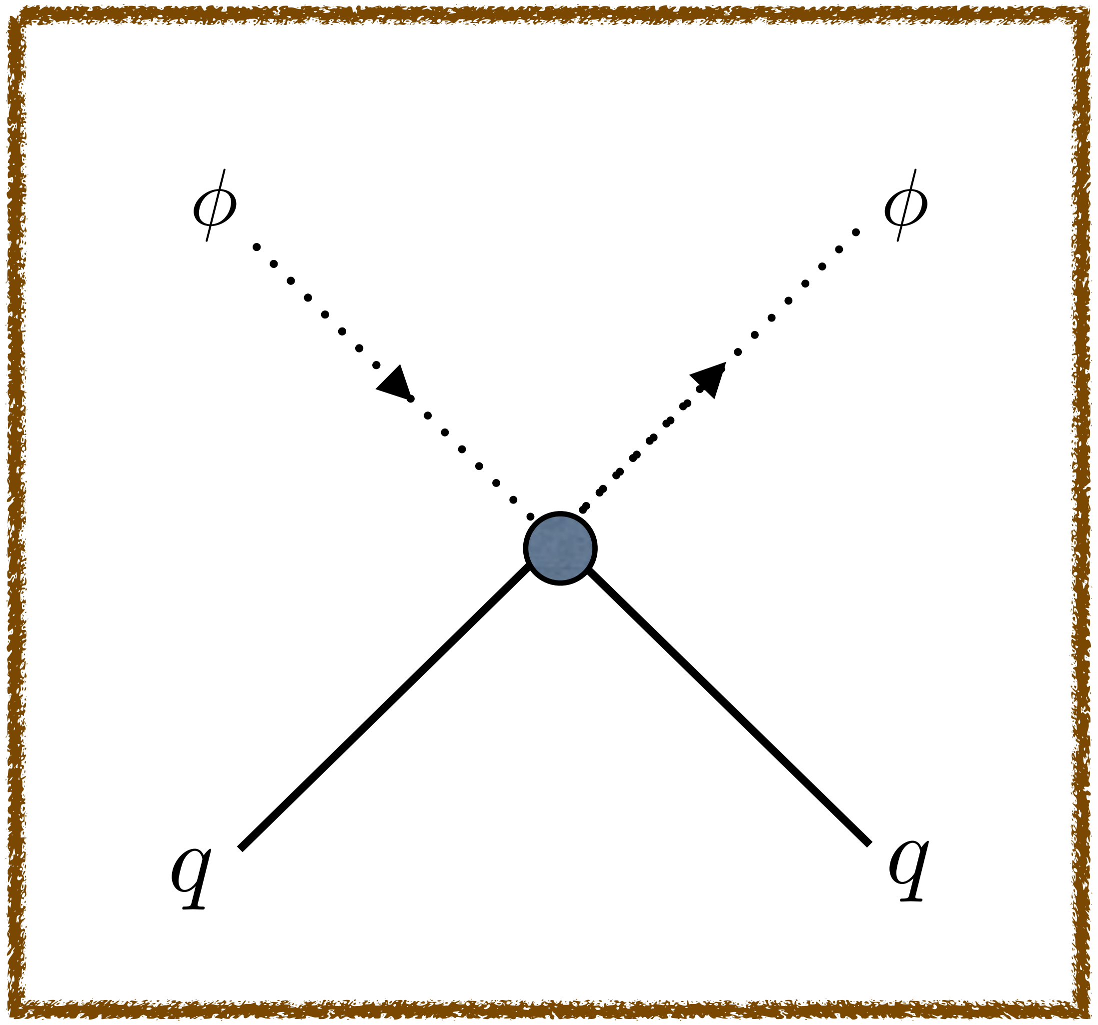
Main questions



How does the direct detection look like?

What kind of models can give this process?

Main questions



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

How does the direct detection look like?

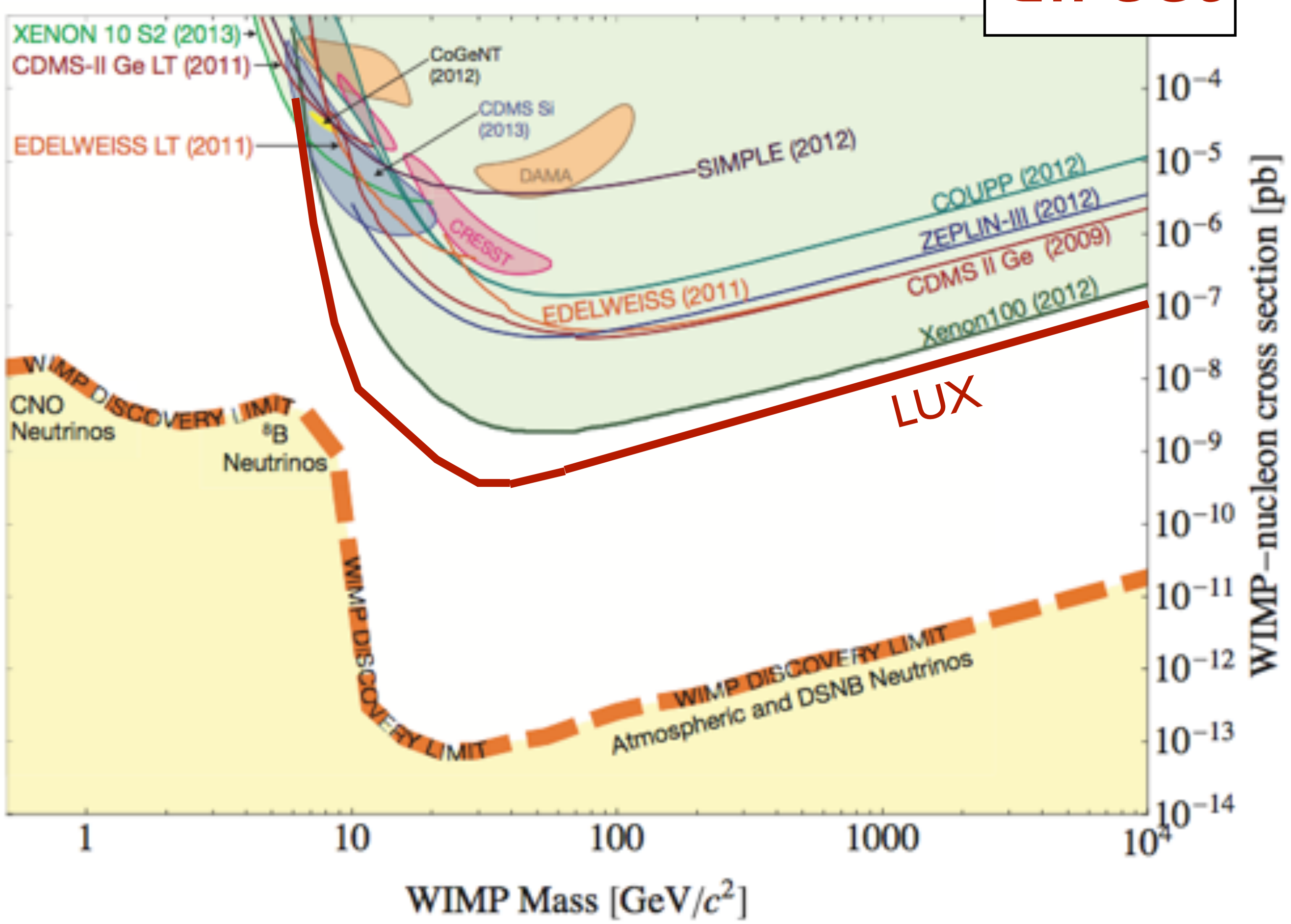
What kind of models can give this process?

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

Current DM experiments

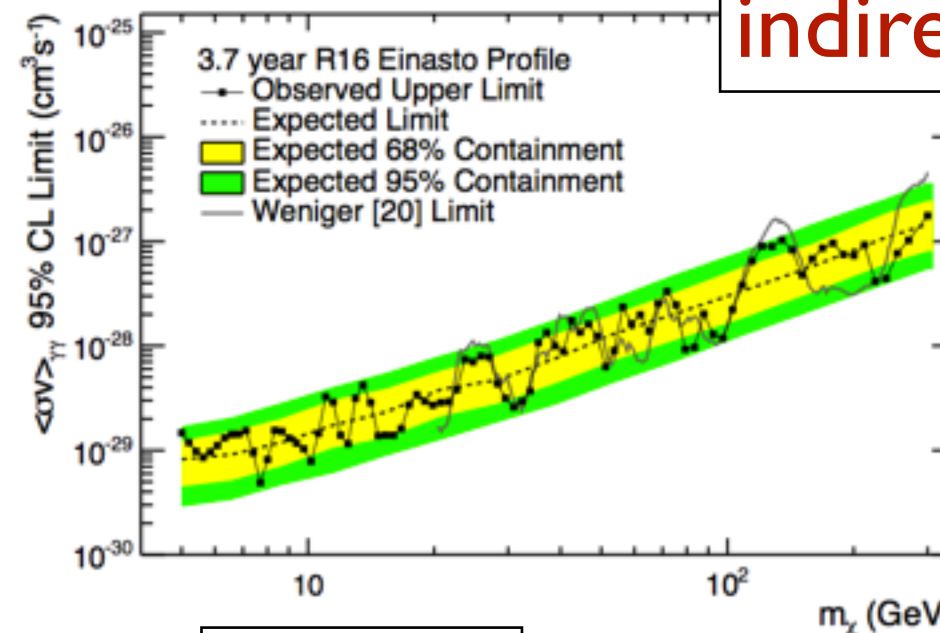
J. Billard and E. Figueroa-Feliciano (13)

direct

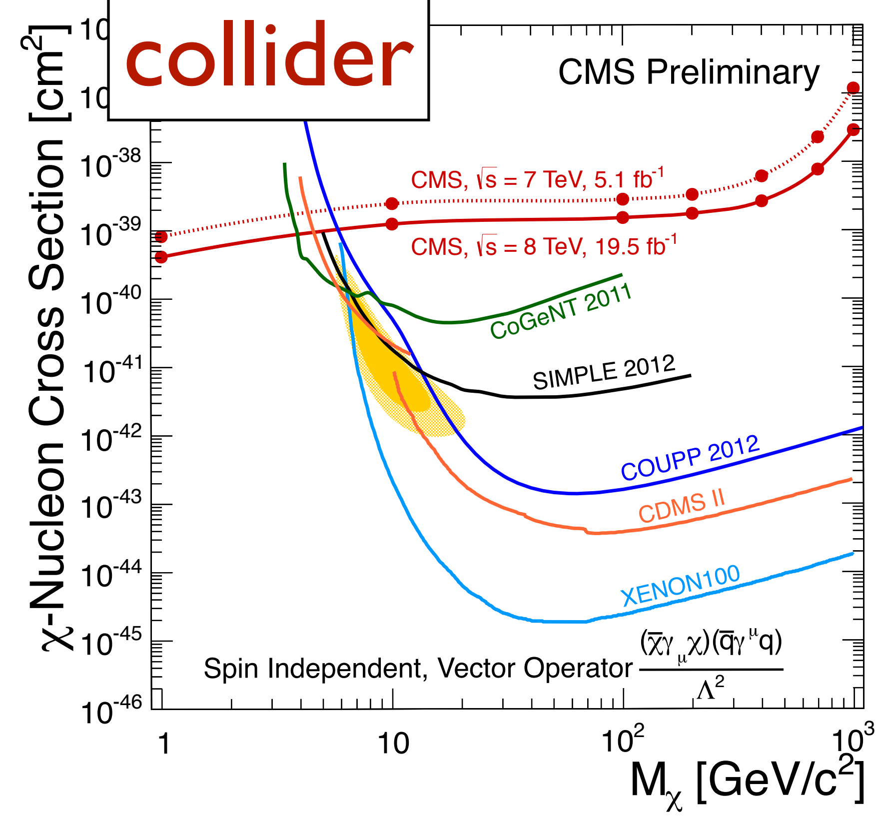


FERMI

indirect



collider



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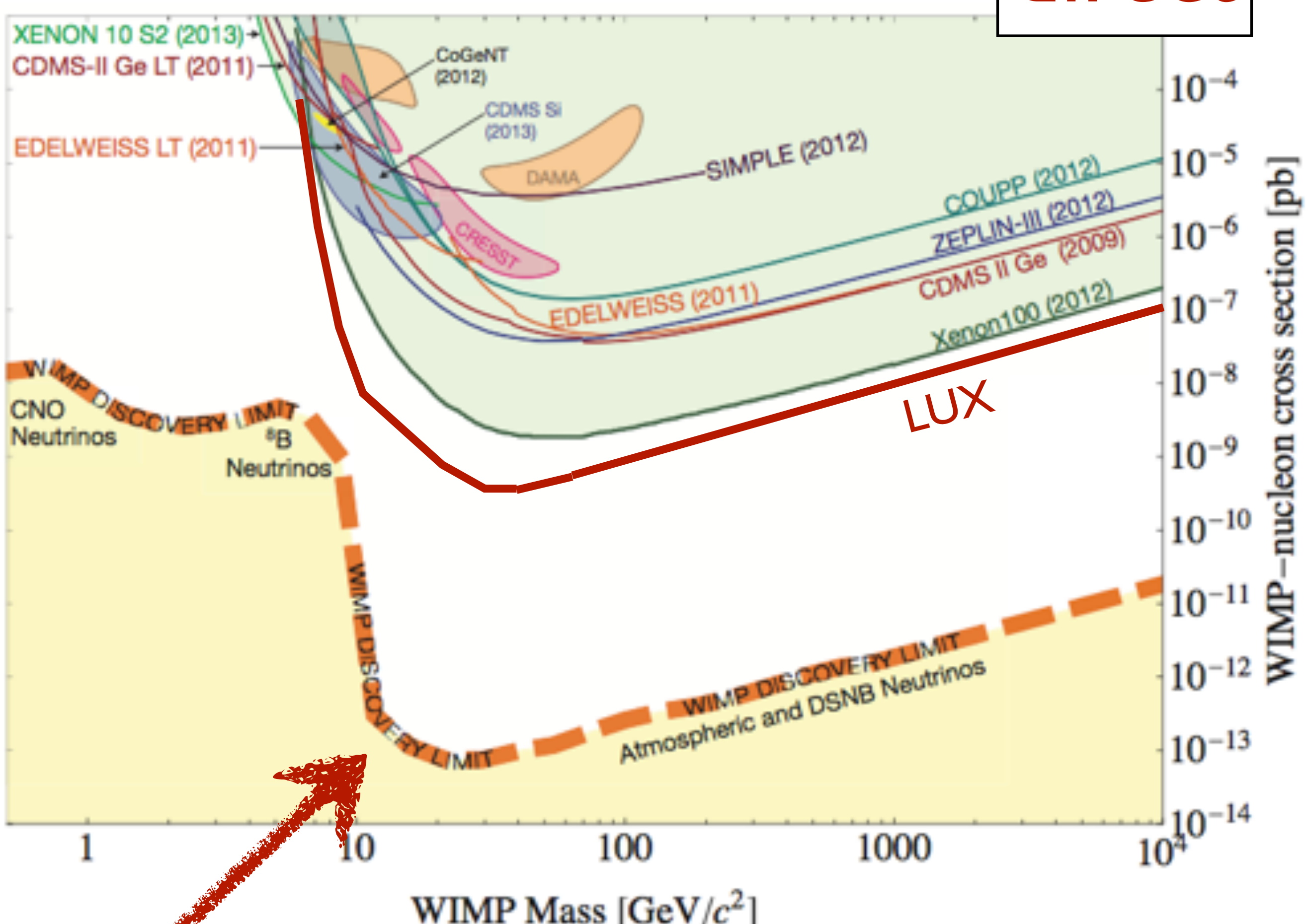
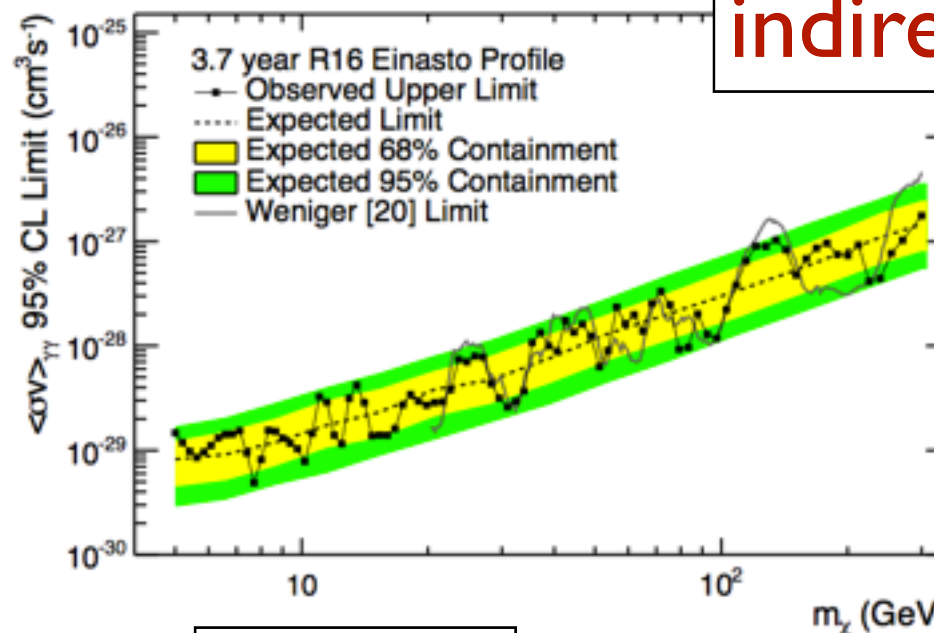


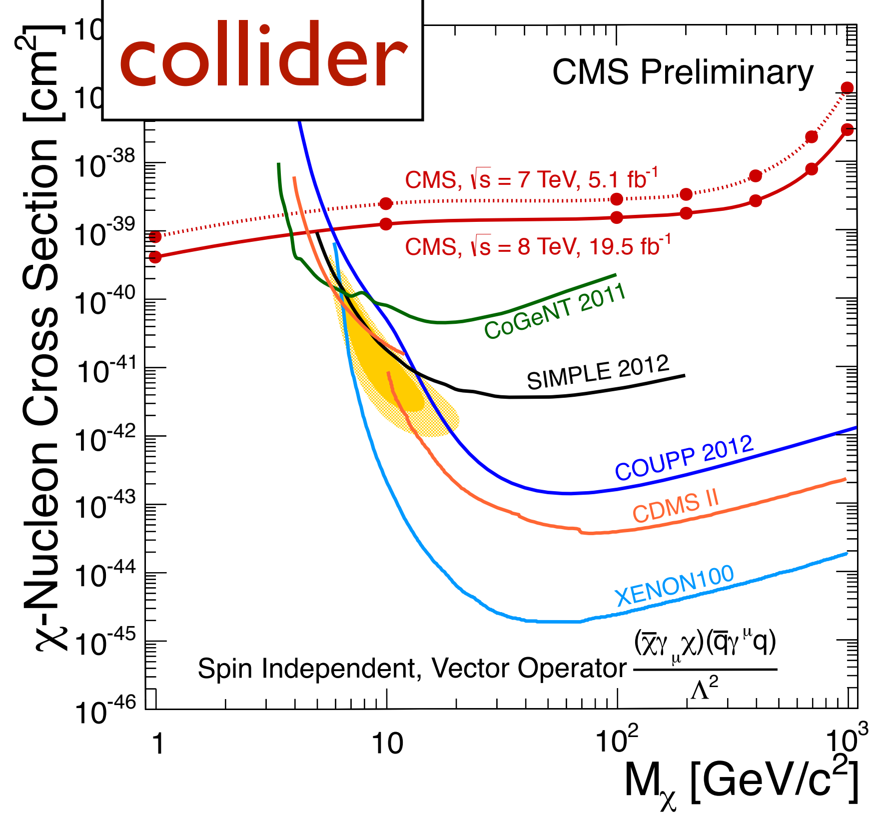
irreducible neutrino-background sets a lower bound on the discovery

FERMI

indirect



collider



Monday, February 10, 2014

Current DM experiments

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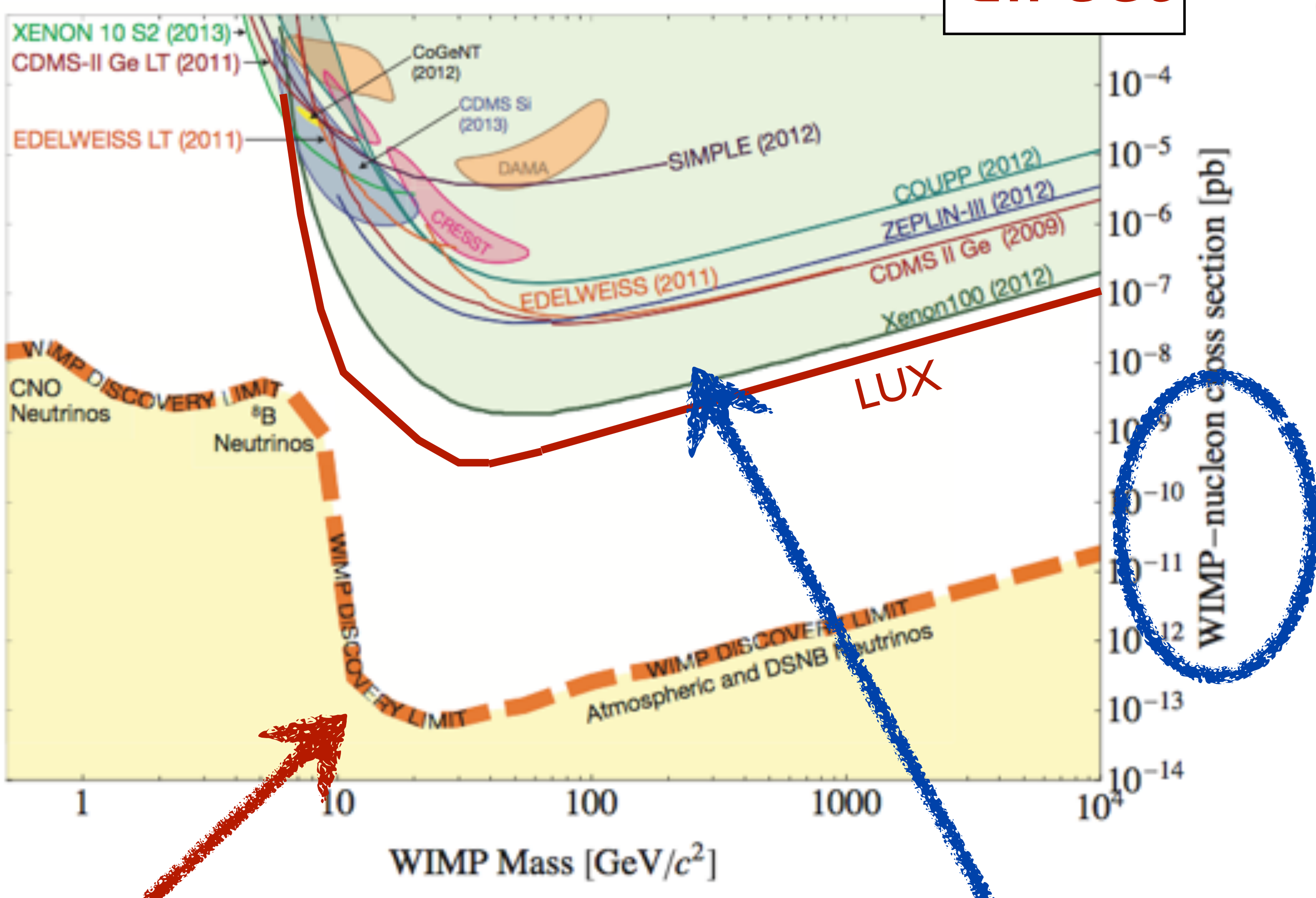
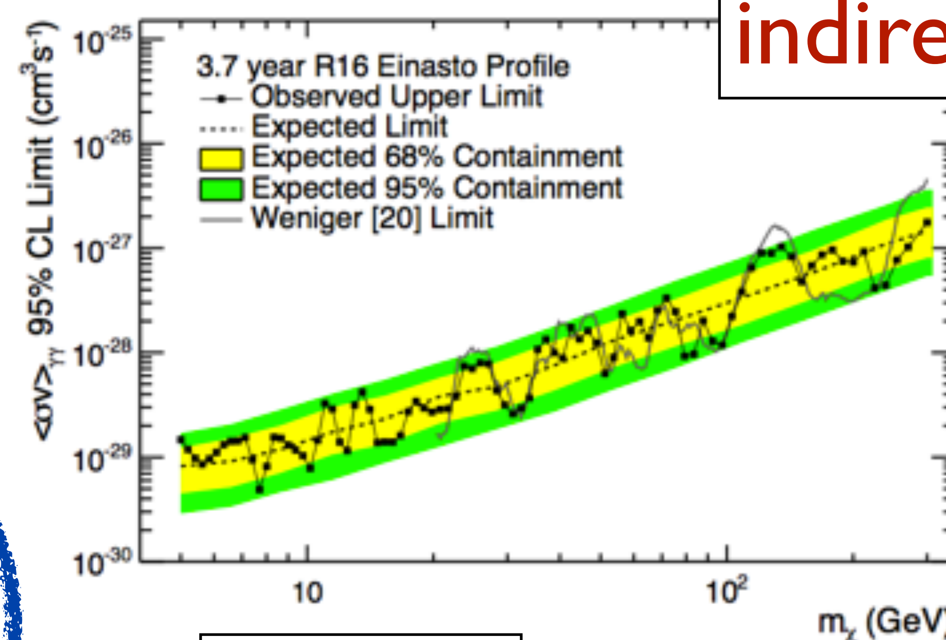
direct



FERMI

indirect



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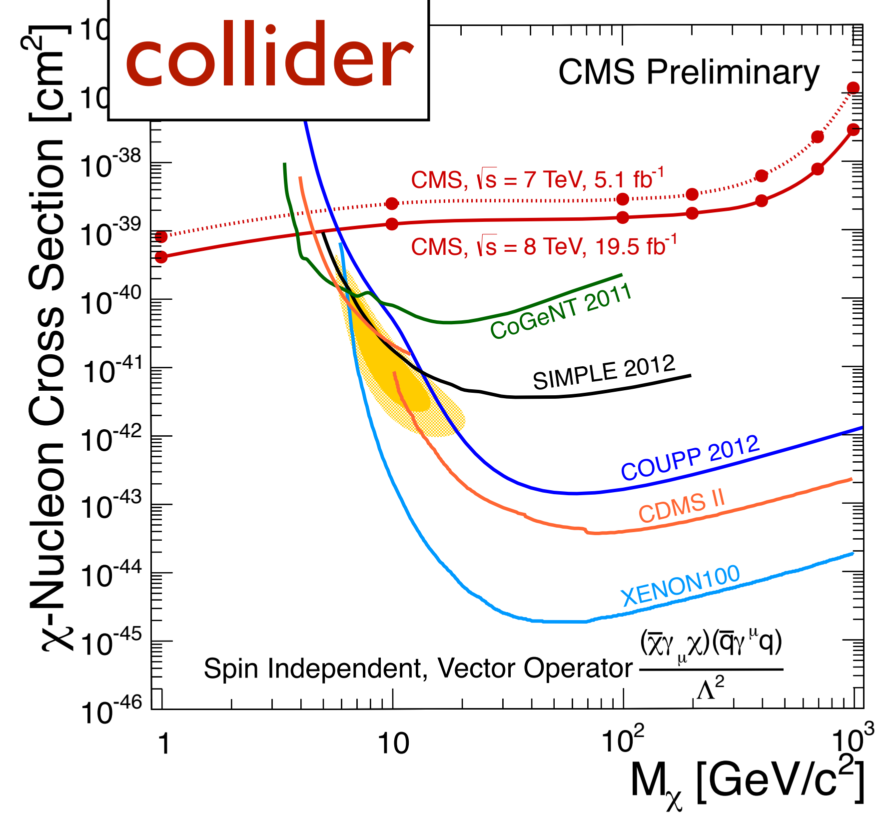
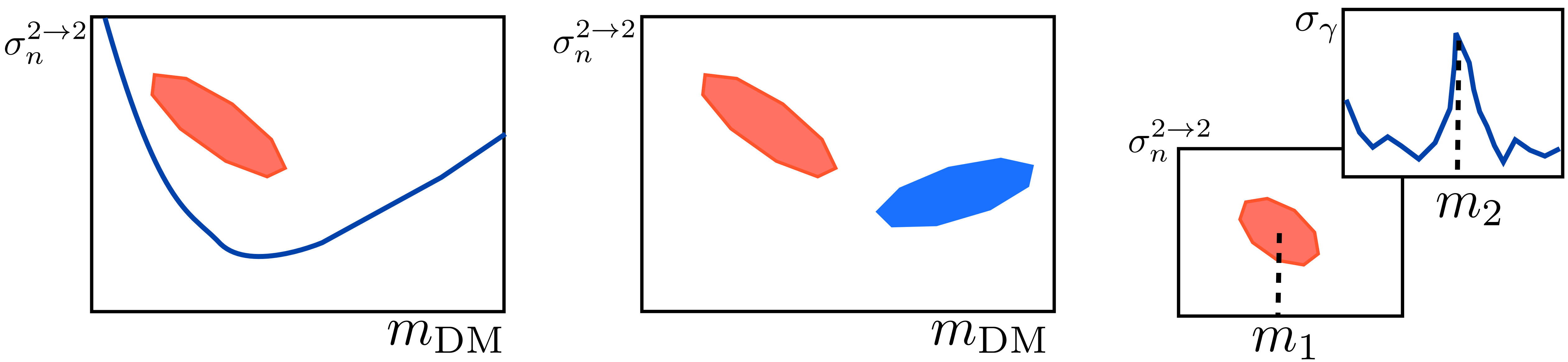


irreducible neutrino-background sets a lower bound on the discovery

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

Useful inconsistencies

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

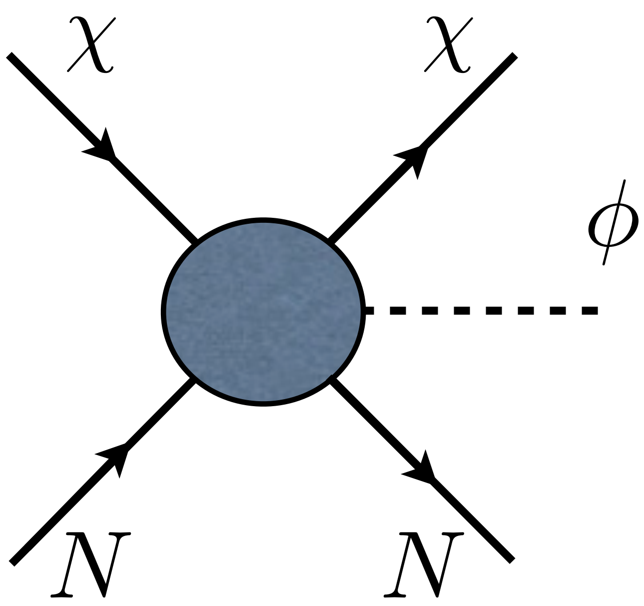


Existing ideas: exothermic DM, isospin violation, non-standard form factors, multi-component DM, ... all assume 2to2 scattering so far

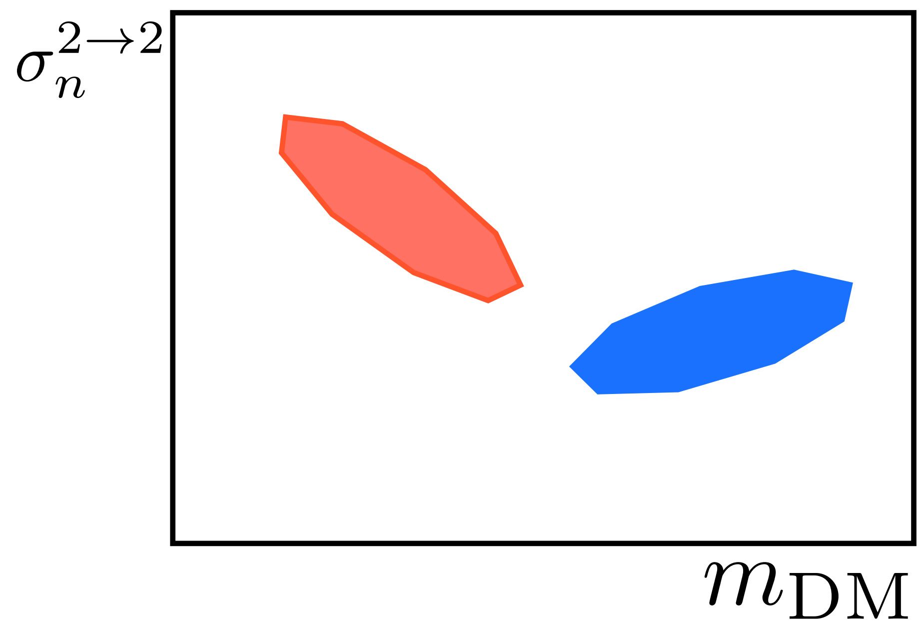
It is important to explore a more complete set of DM models to explain the future data

Missing ingredient: different topology

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



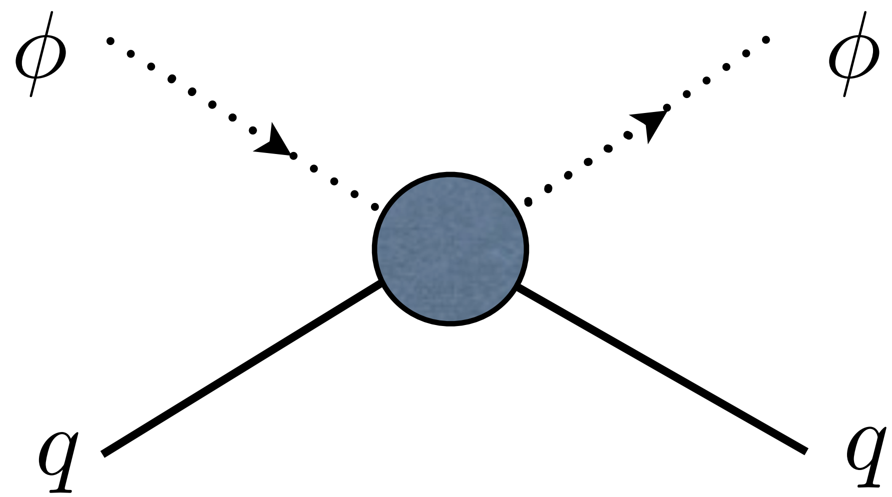
for example



- 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



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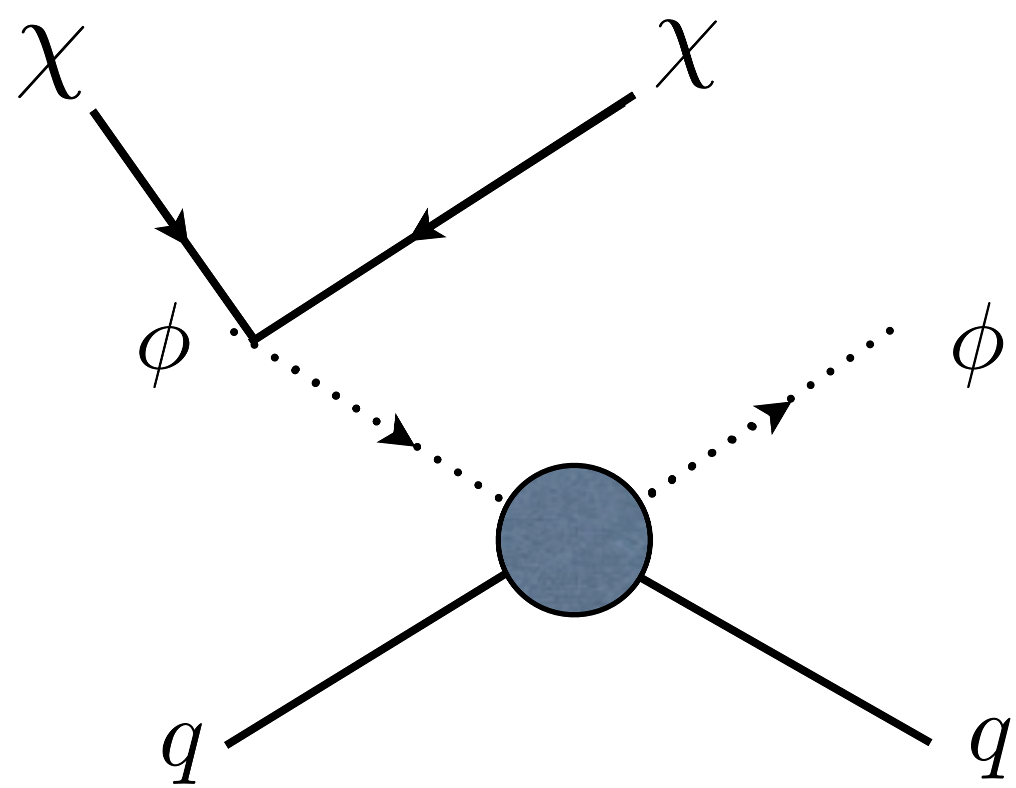
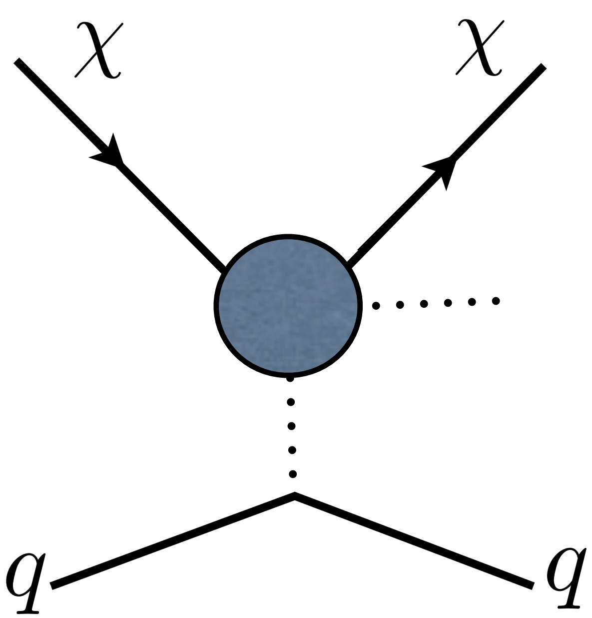


dark **m**ediator **D**ark **M**atter

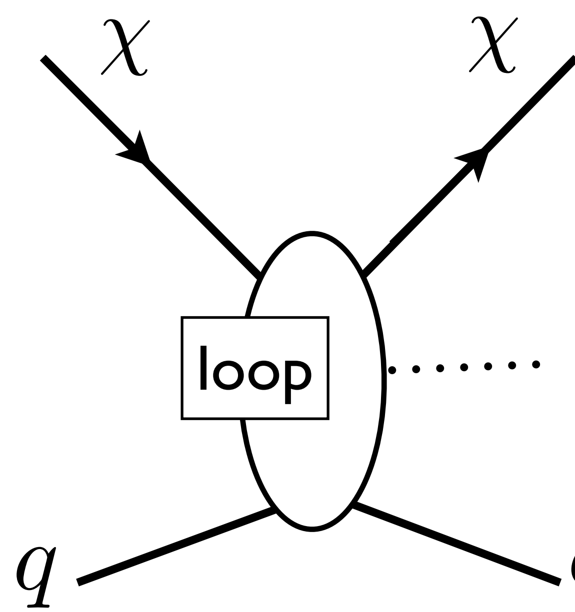
A natural way to have the 2 to 3 scattering

Other ways of getting 2to3 ?

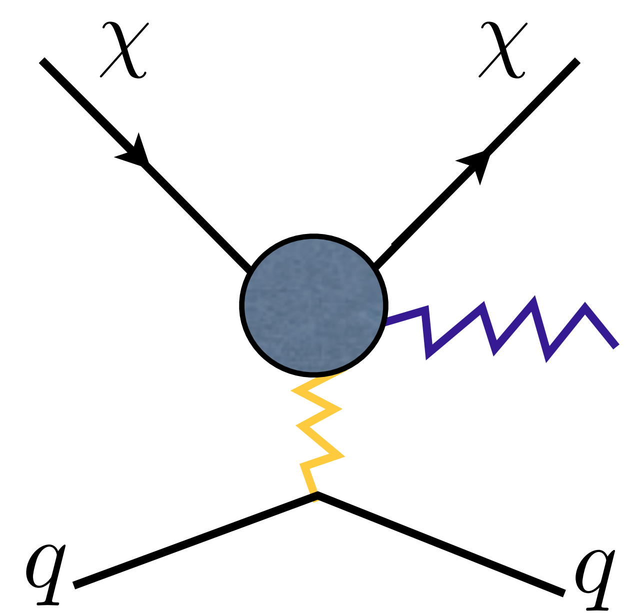
Not easy...



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



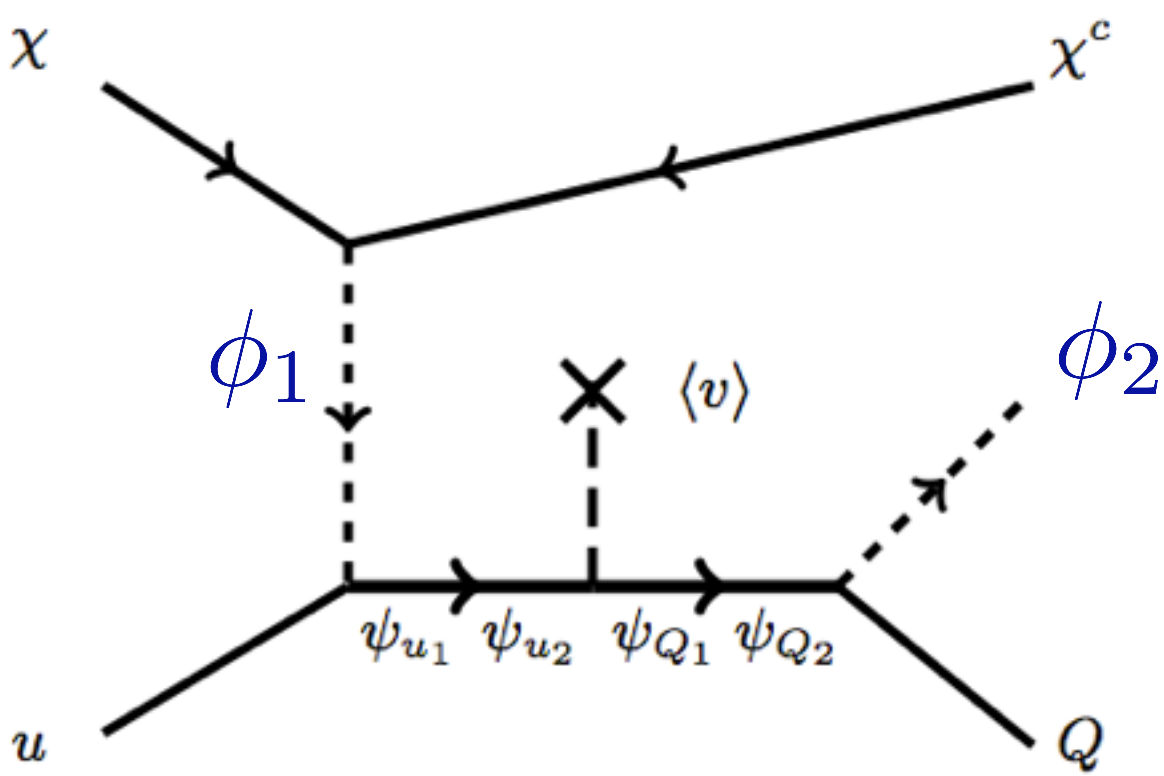
the loop suppression makes it hard to have a large cross section



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
ϕ	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	$-1/3$	$2\pi/3$
χ	1	1	0	$2\pi/3$

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

- 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 ϕ 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

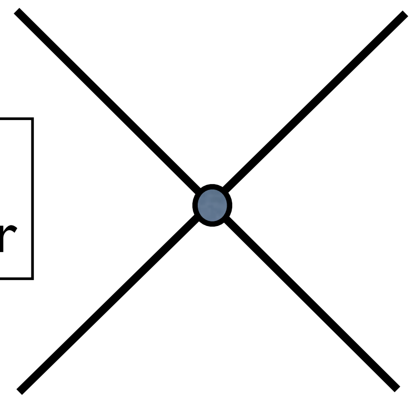
for 2 to 2 contact operator

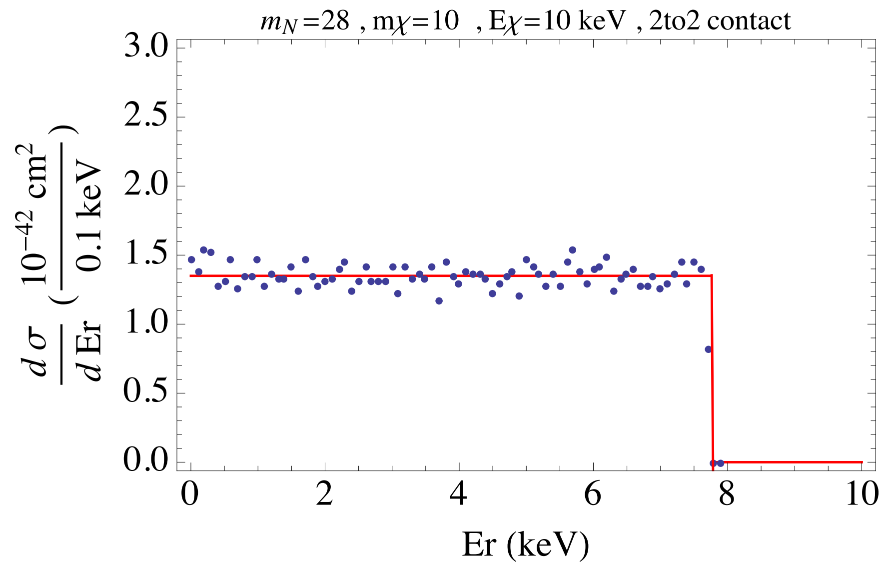
$$\frac{dR}{dE_r} = N_T \frac{\rho_\chi}{m_\chi} \int dv \; v f(v) \frac{d\sigma_N}{dE_r} \quad \longrightarrow \quad \frac{dR}{dE_r} = \frac{1}{2} \frac{\sigma_n^{\mathrm{SI}}}{\mu_{n\chi}^2} N_T \rho_\chi \frac{m_N}{m_\chi} A^2 F^2(E_r) \int_{v_{min}(E_r)}^{v_{max}} dv \; \frac{1}{v} f(v)$$

Recoil energy spectrum

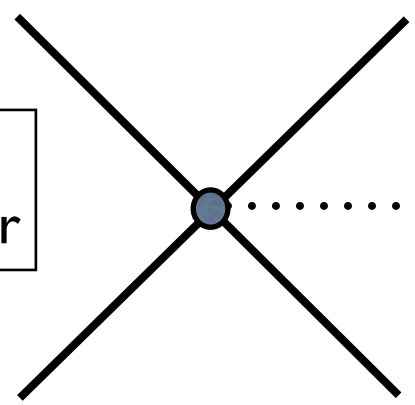
For a given DM energy

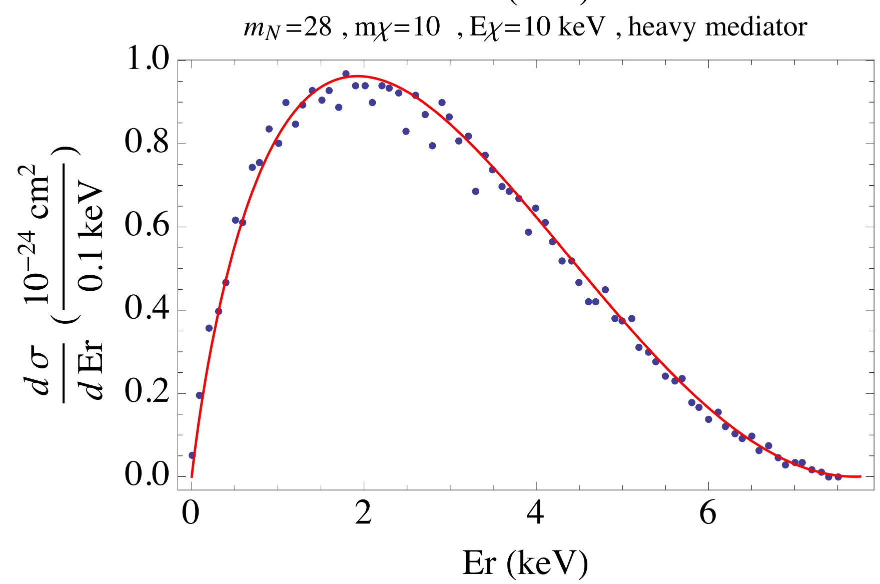
standard 2 to 2
contact operator



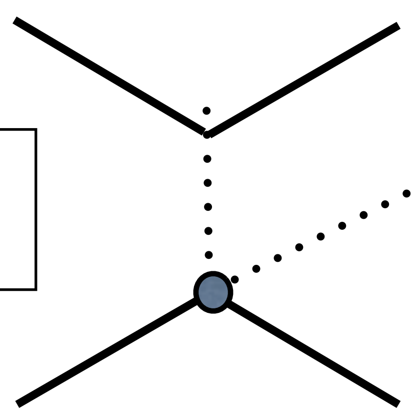


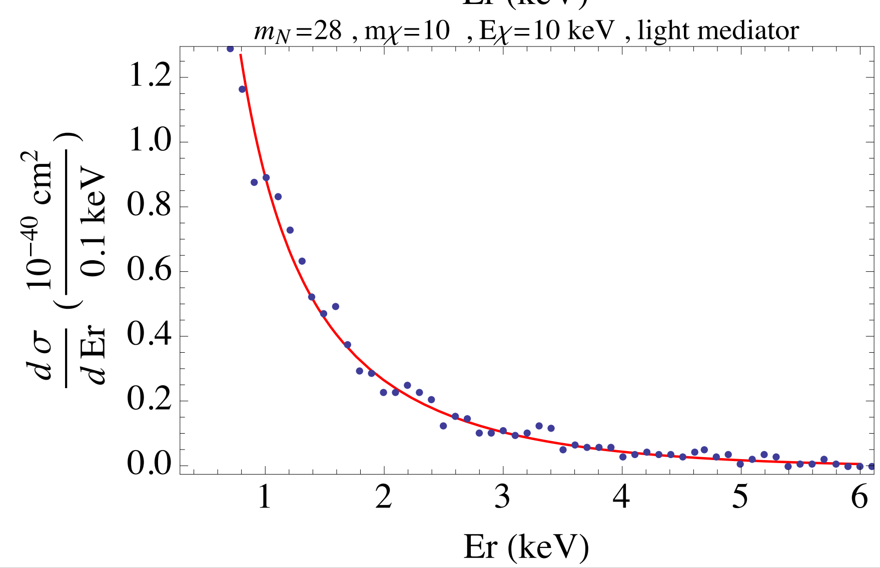
2 to 3
contact operator





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
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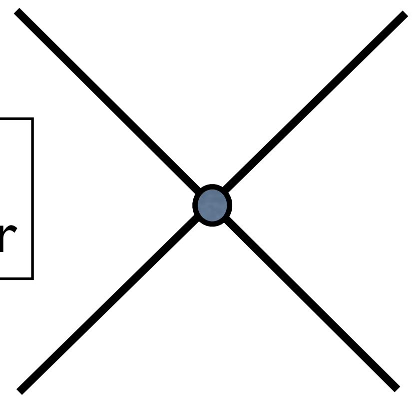

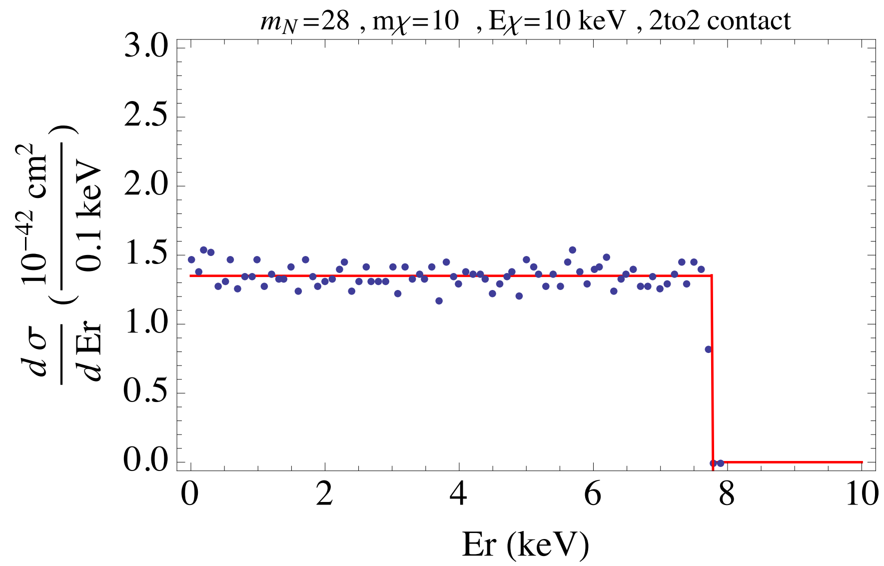

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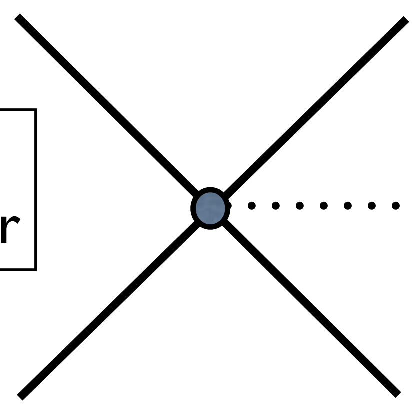

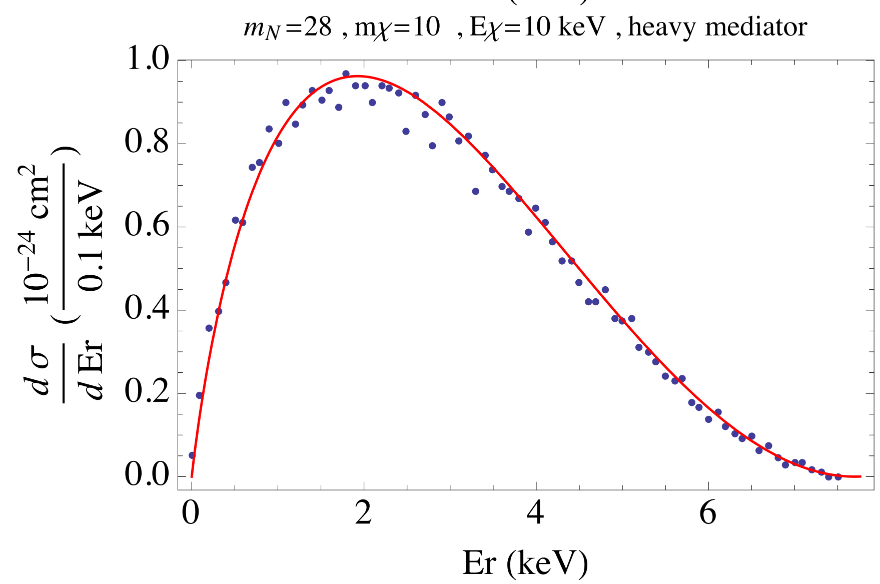

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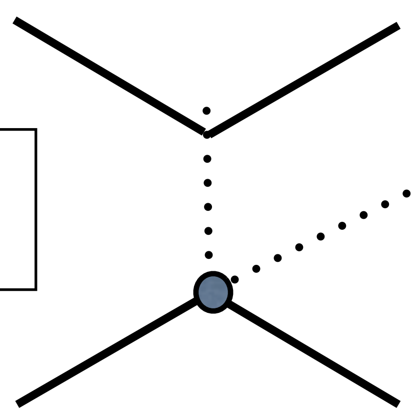

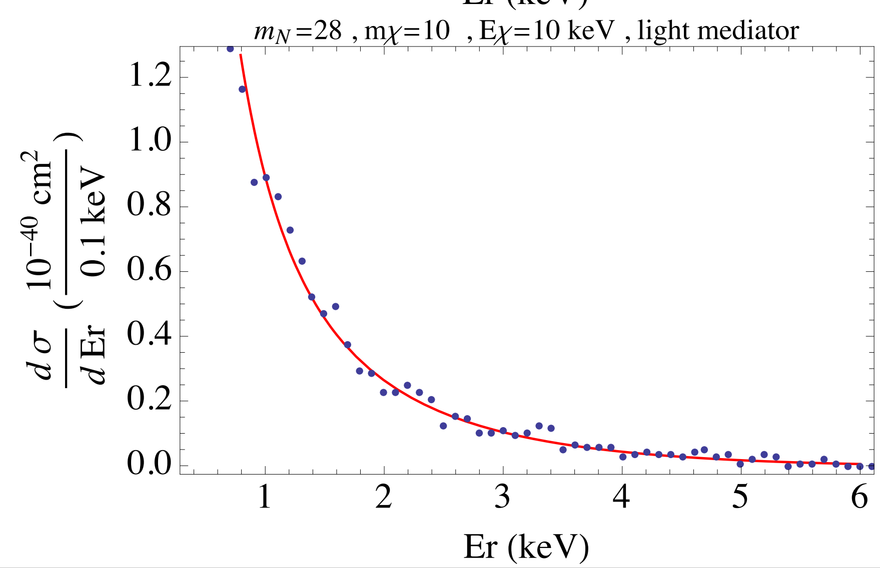

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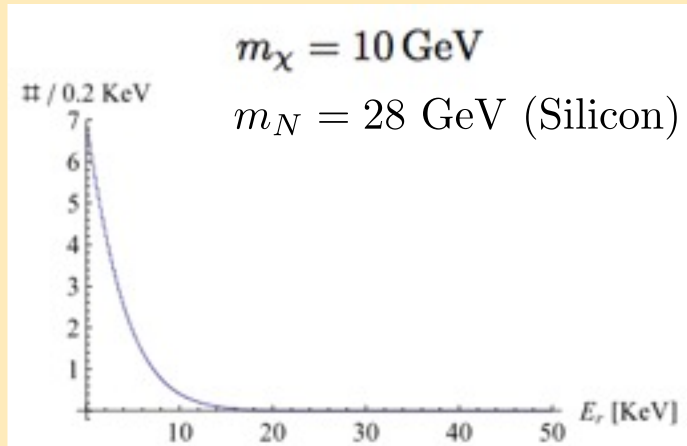
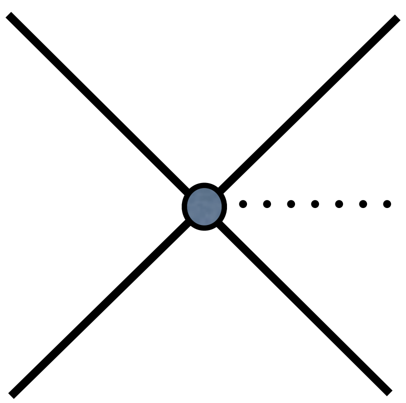
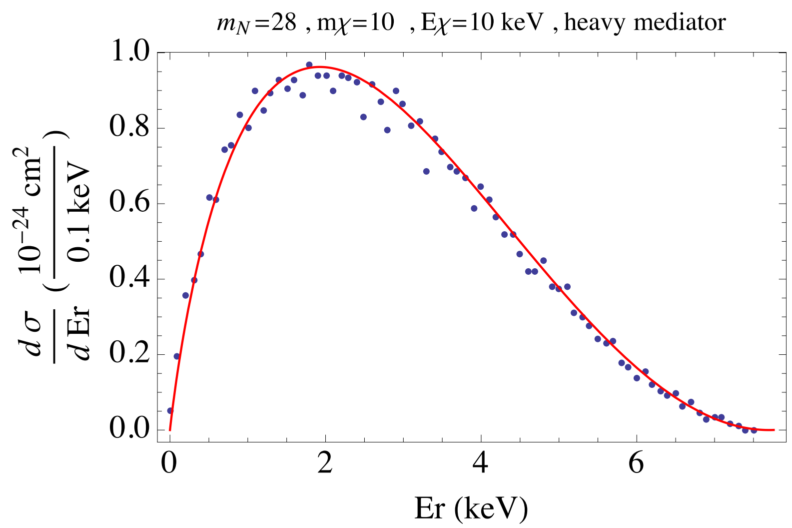
$$E_r^{max} = \frac{2\mu_{N\chi}^2}{m_N} v^2$$

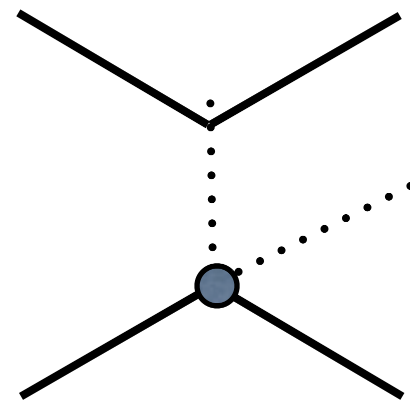
2to2 after f(v) and F

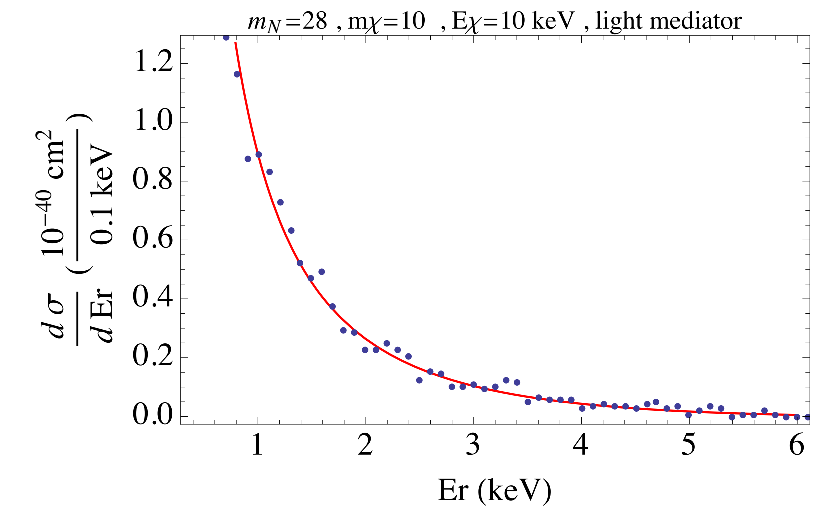


2to3 scattering: contact vs. dmDM

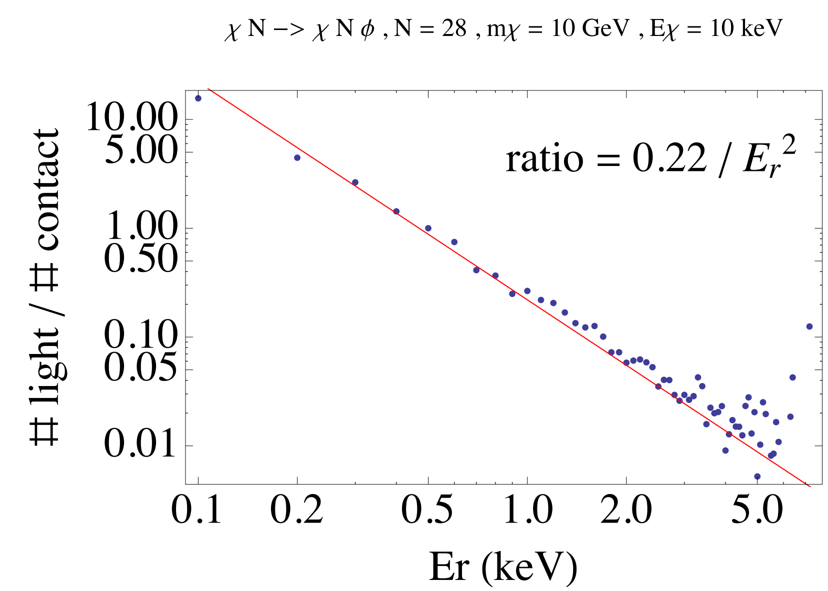






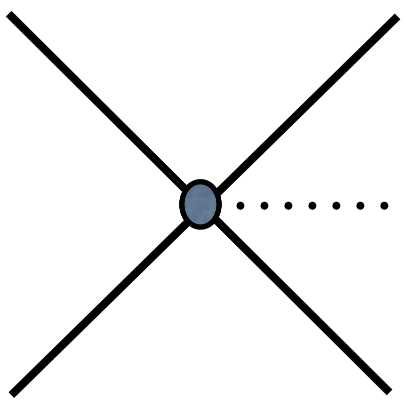


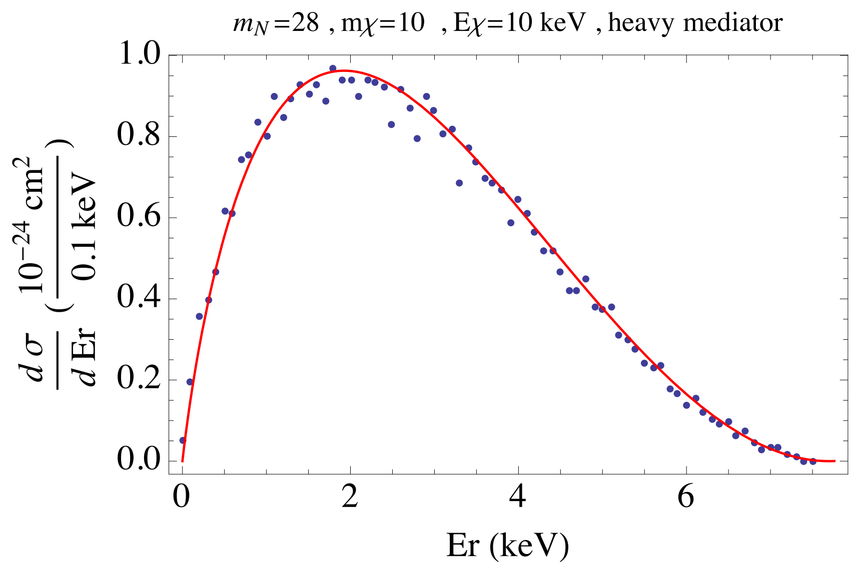
$$\frac{\left.\frac{d\sigma_{2\to3}}{dE_R}\right|_{light}}{\left.\frac{d\sigma_{2\to3}}{dE_R}\right|_{heavy}} \propto \frac{m_\Phi^4}{(m_N\,E_R)^2} \propto \frac{m_\Phi^4}{|\vec{p}_N|^4}$$



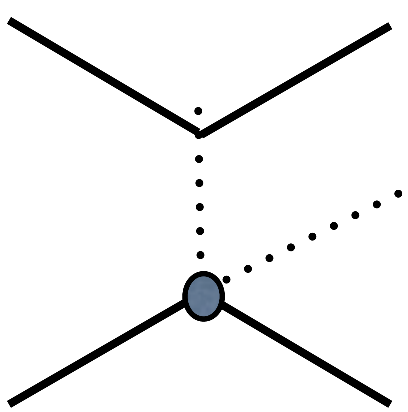
coming from the light mediator's propagator

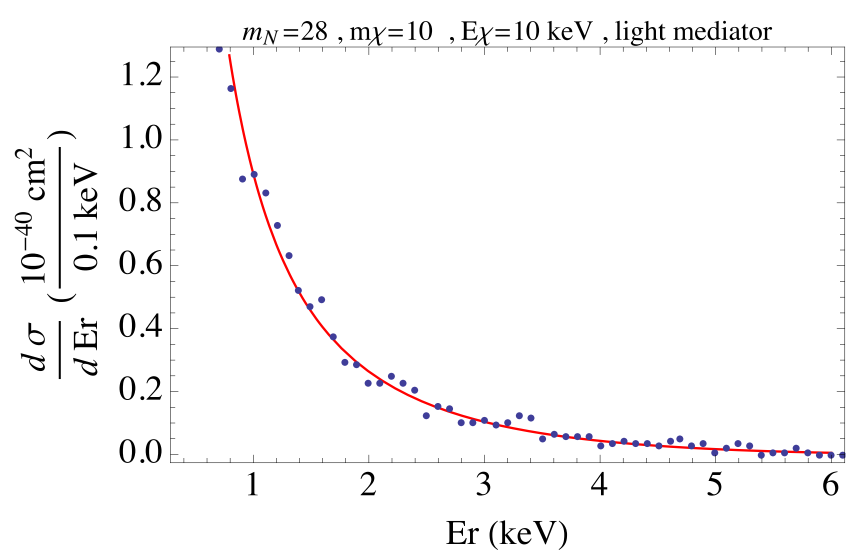
Approximation of the spectrum





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





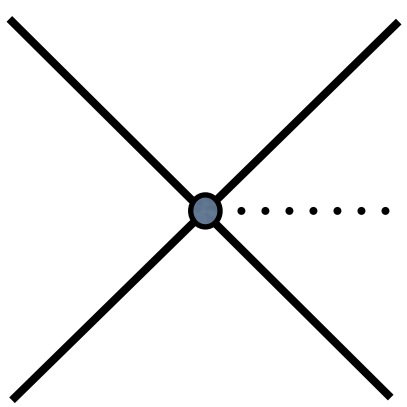
$$\propto E_R^{-1} \left(1 - \sqrt{E_R/E_R^{max}}\right)^2$$

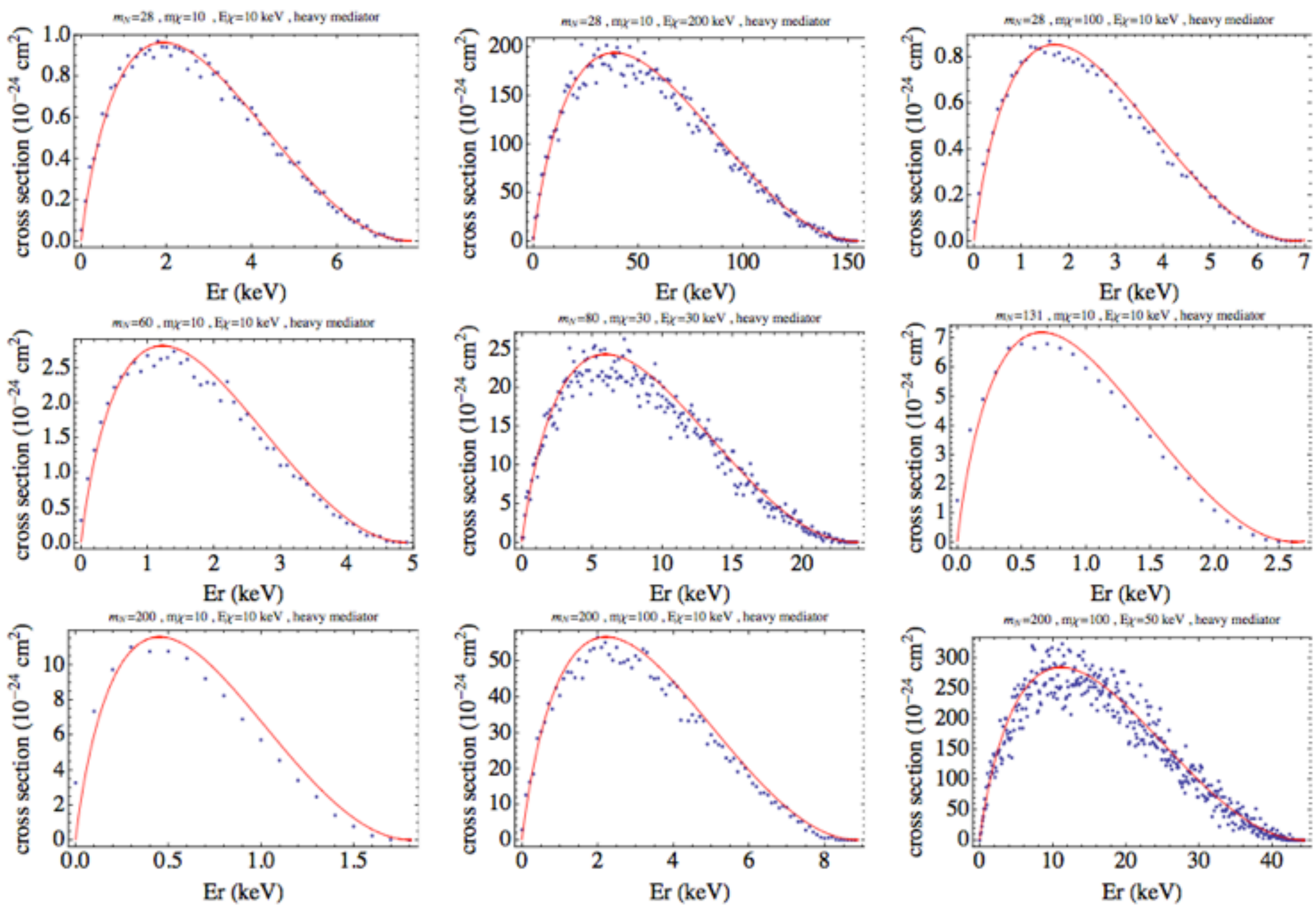
with $$E_R^{max} = \frac{\mu_{\chi N}^2}{2\, m_N}\, v^2$$

A nice description of the Erecoil

$$\frac{d\,\sigma_{2\to3}^{contact}}{d\,E_R} \simeq constant \times \left(\frac{m_N}{\mathrm{GeV}}\right)^2 \times \left(\frac{E_R}{\mathrm{keV}}\right)\left(1-\sqrt{E_R\,/\,E_R^{max}}\right)^2, \quad E_R^{max} = 2\,\frac{\mu_{\chi N}^2}{m_N}\,v^2$$

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

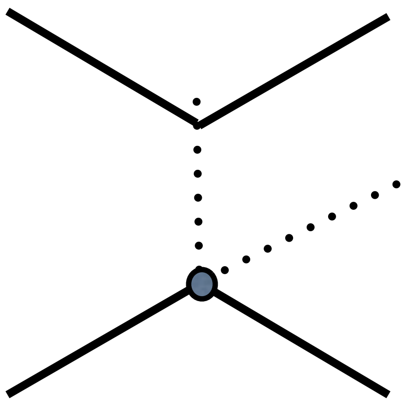


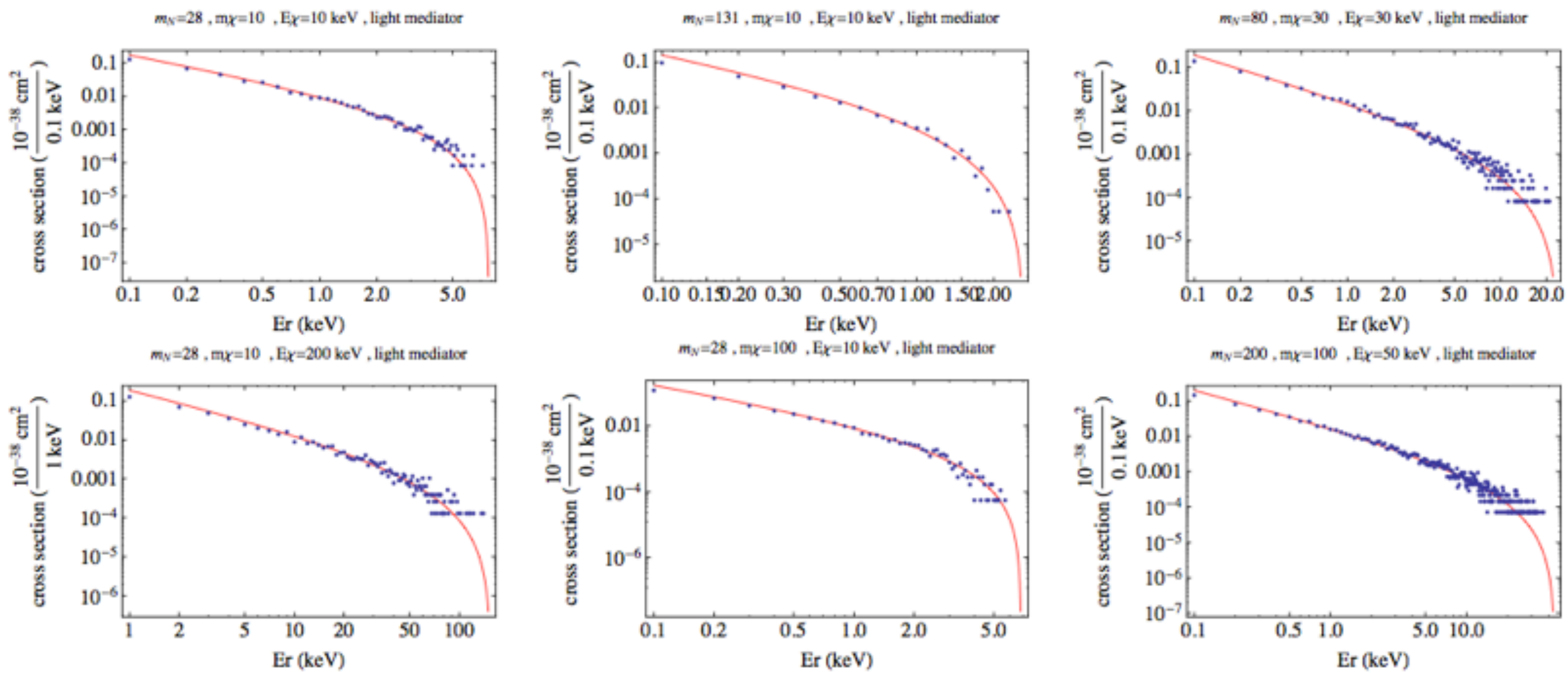


A nice description of the Erecoil

$$\frac{d\,\sigma^{light}_{2\to3}}{d\,E_R} \simeq constant \times \left(\frac{E_R}{\mathrm{keV}}\right)^{-1} \left(1 - \sqrt{E_R\,/\,E_R^{max}}\right)^2, \quad E_R^{max} = 2\,\frac{\mu^2_{\chi N}}{m_N}\,v^2$$

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





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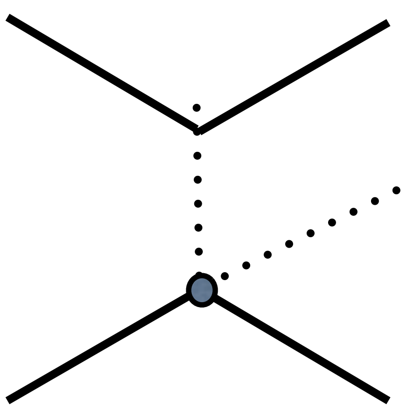
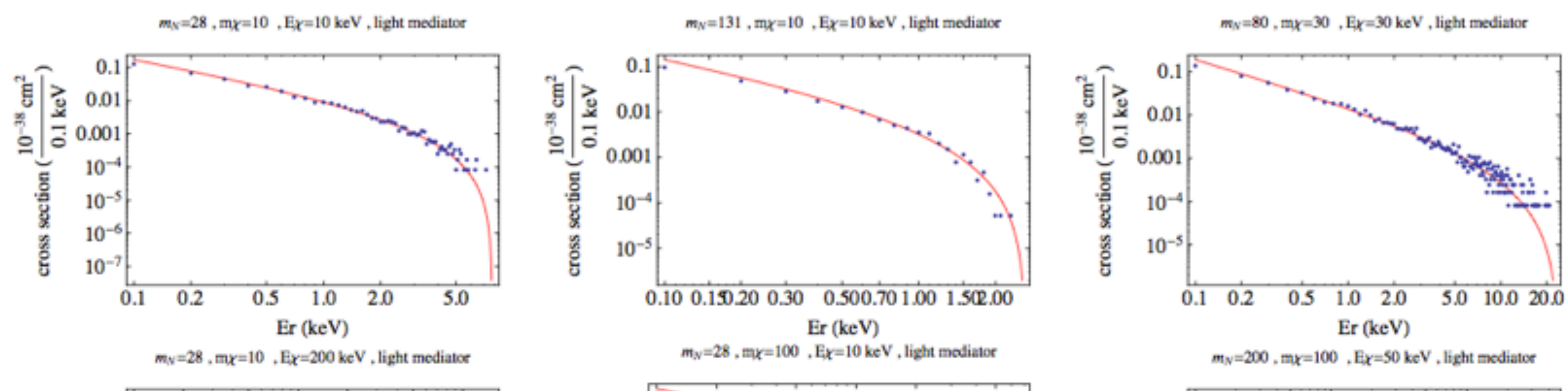
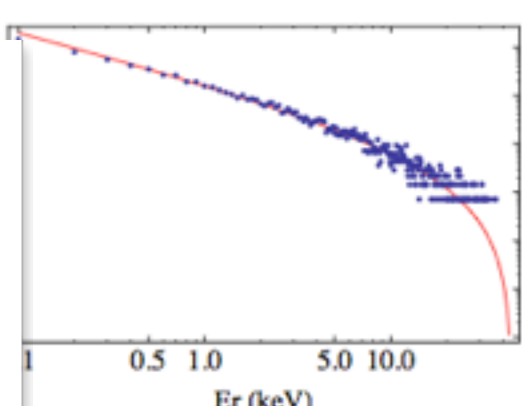






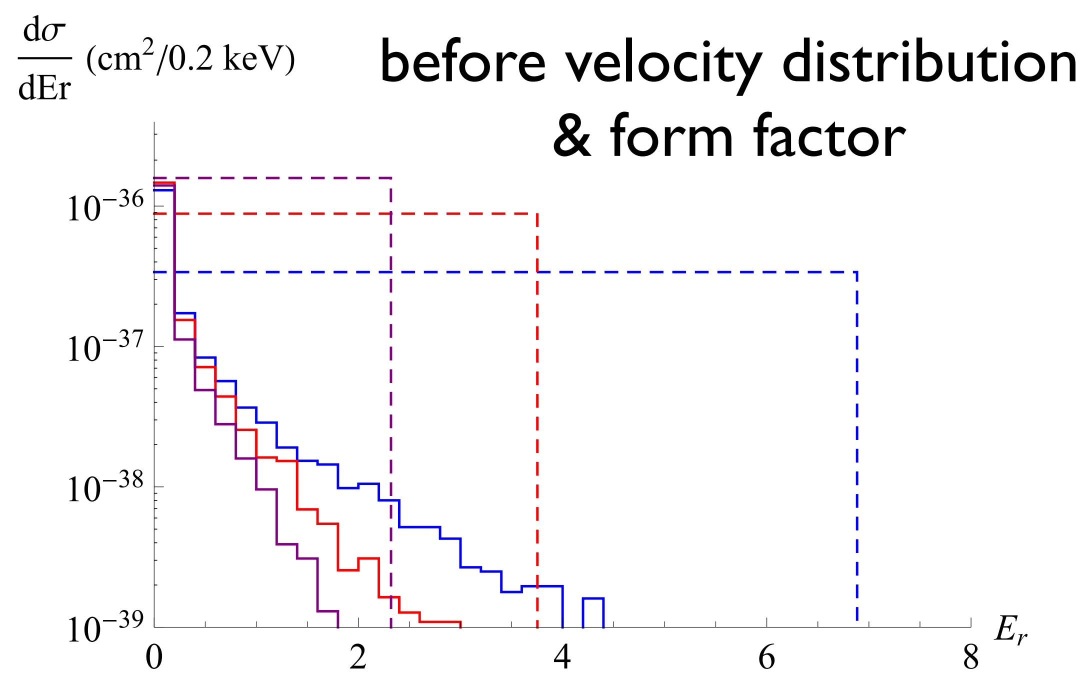
Three ingredients give the spectrum

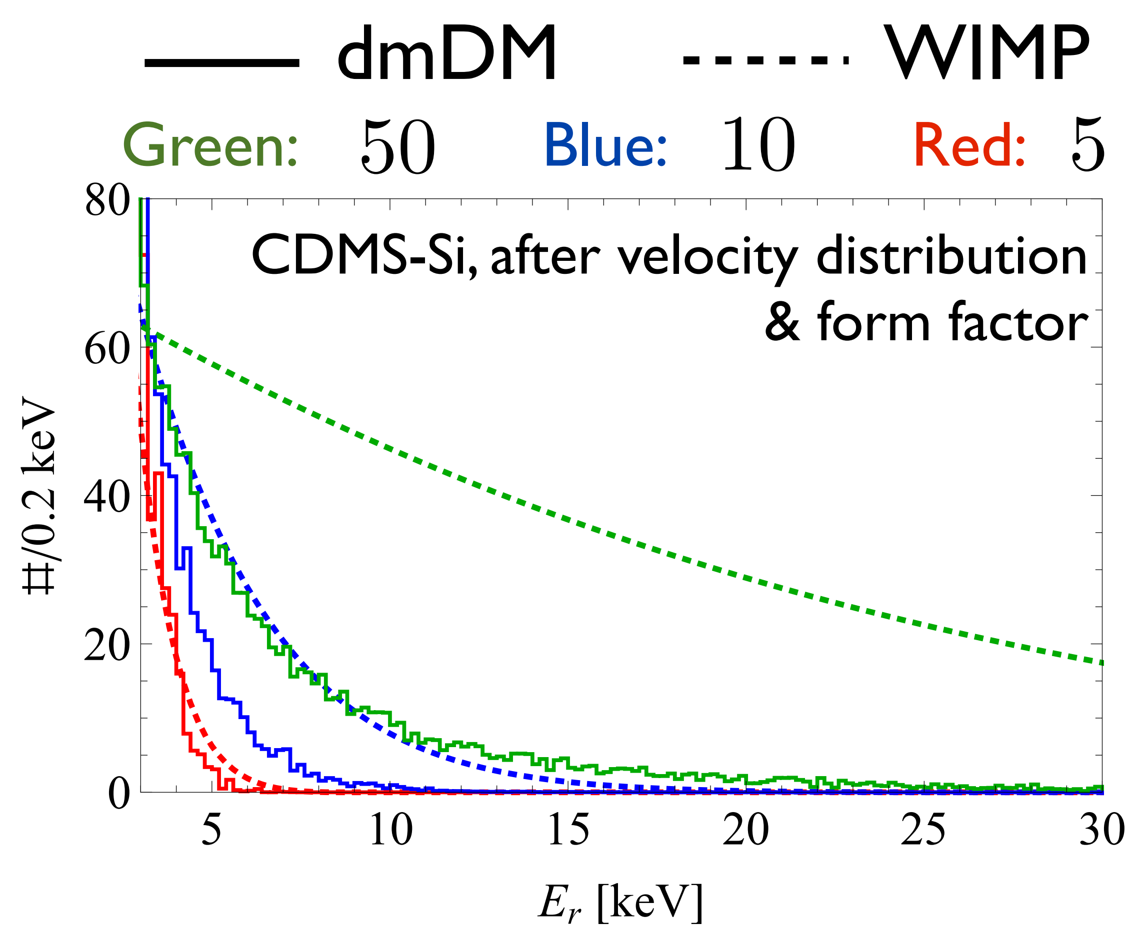
I. phase space with ϕ carrying away some energy

II. E_R^{max} relates to the DM-nucleus mass

III. E_R^{-2} from the propagator of light mediator

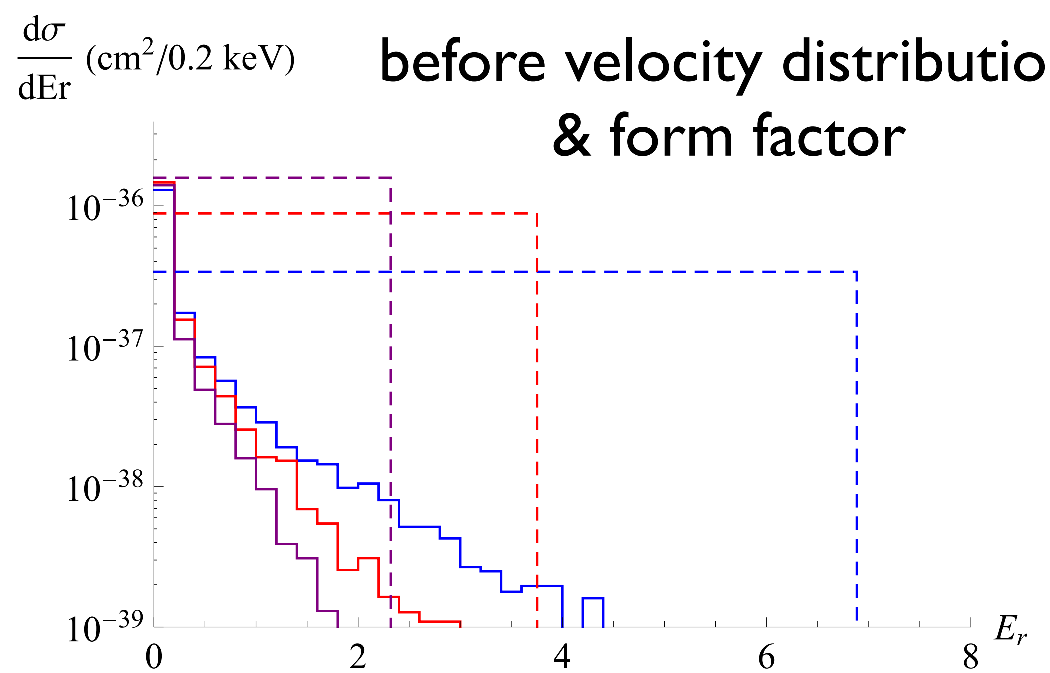
Mappings between 2to2 & 2to3

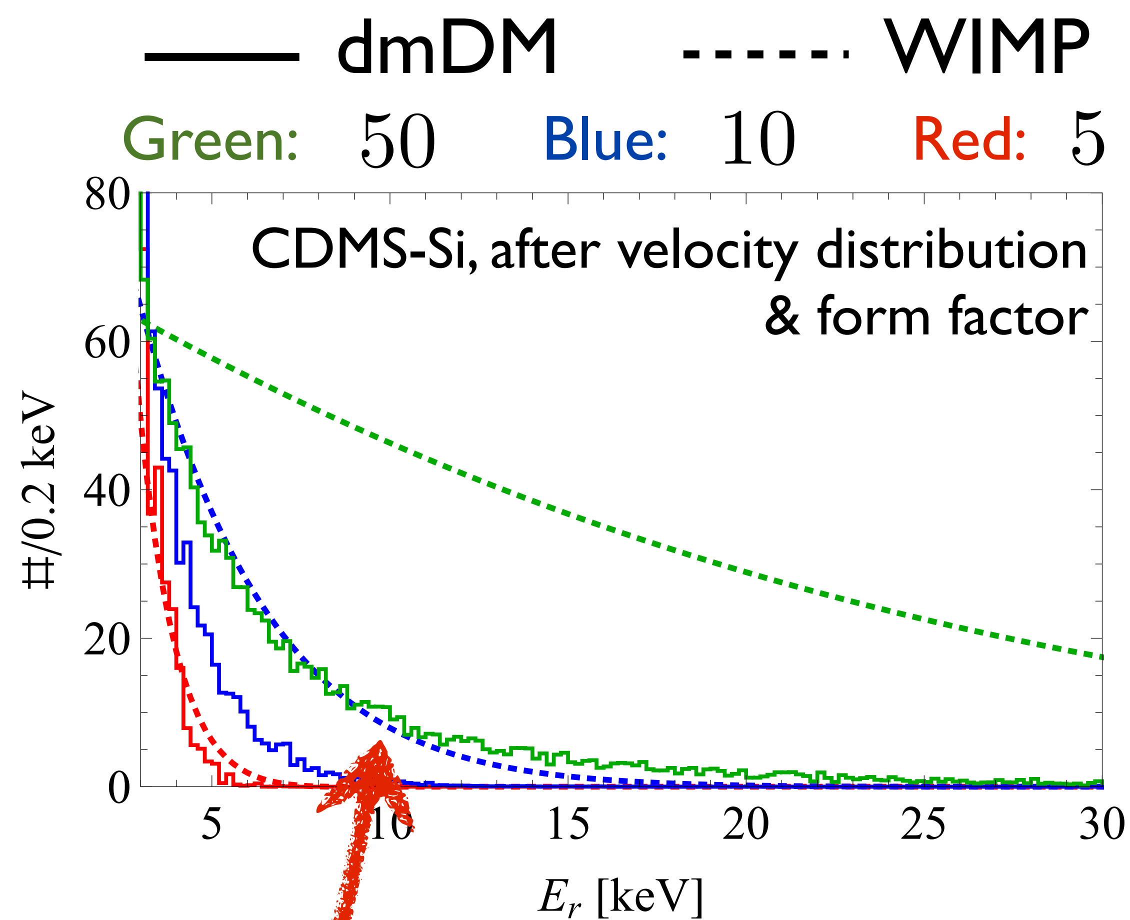




- lack of events makes it hard to distinguish the shape difference in detail
- heavy dmDM looks like a light WIMP DM
- since the m_χ of dmDM only shows up in $\mu_{\chi N}$ of the spectrum, the spectrum is insensitive to the DM mass when the true $m_\chi \gg \mu_{\chi N}$

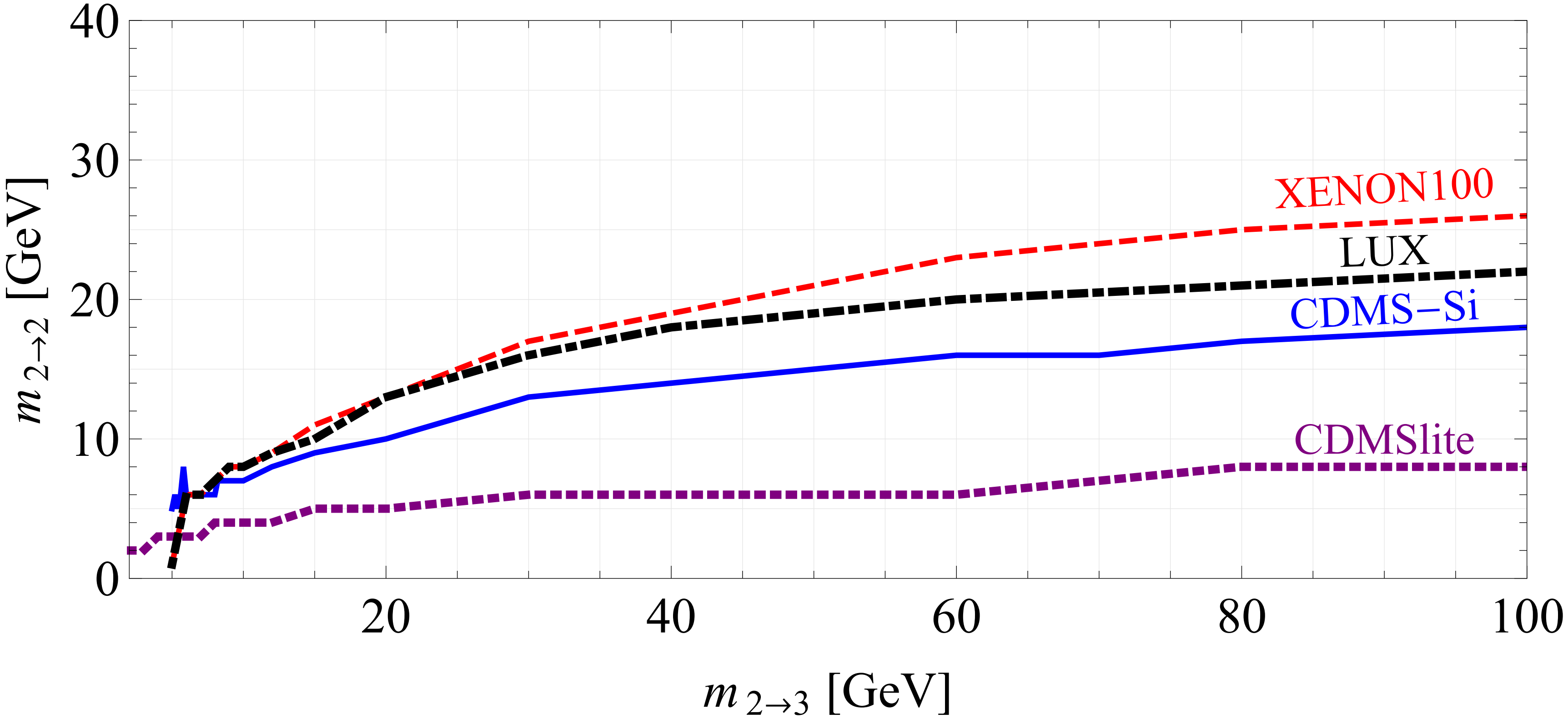
Mappings between 2to2 & 2to3





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

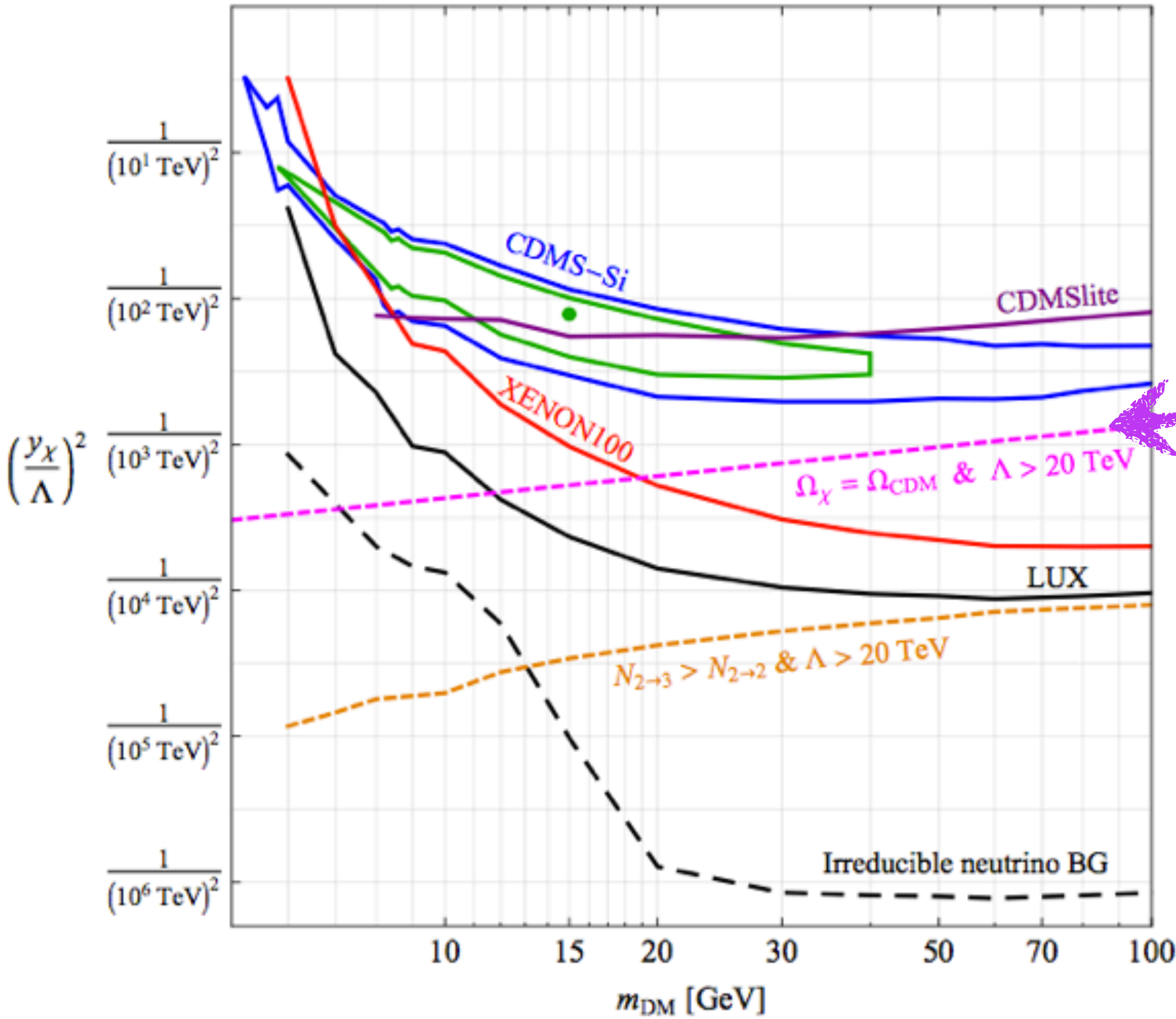
Pseudo-light Dark Matter

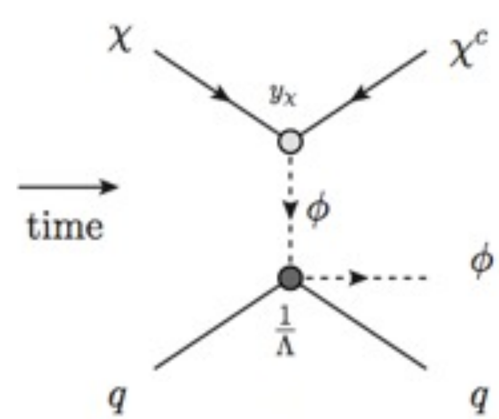


- 100 GeV DM fakes a 10 GeV WIMP
- different masses obtained by different experiments

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

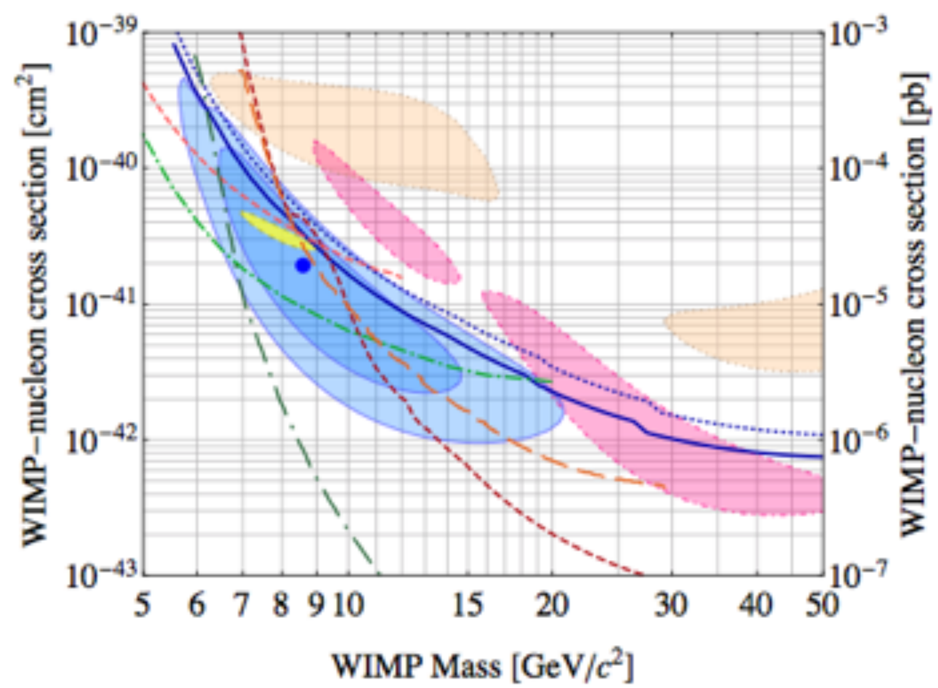
Interaction vs. mass





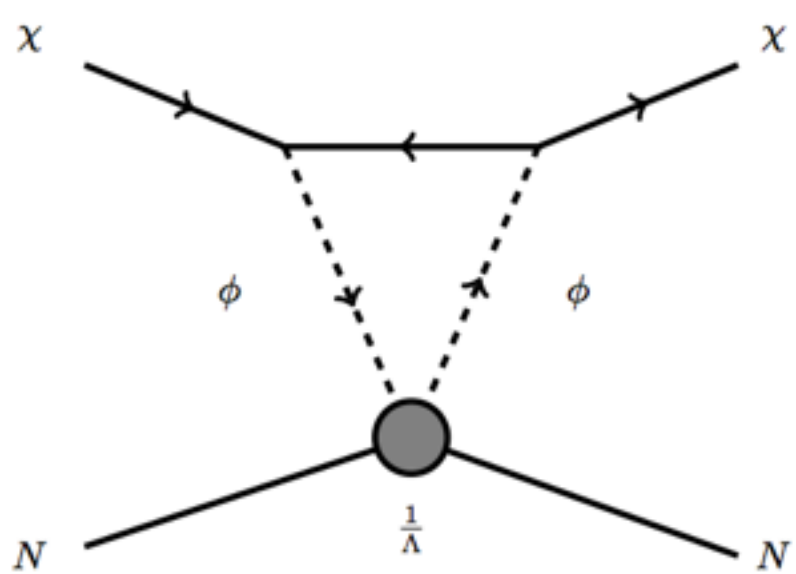
$$\sigma \propto \left|\frac{y_\chi}{\Lambda}\right|^2$$

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



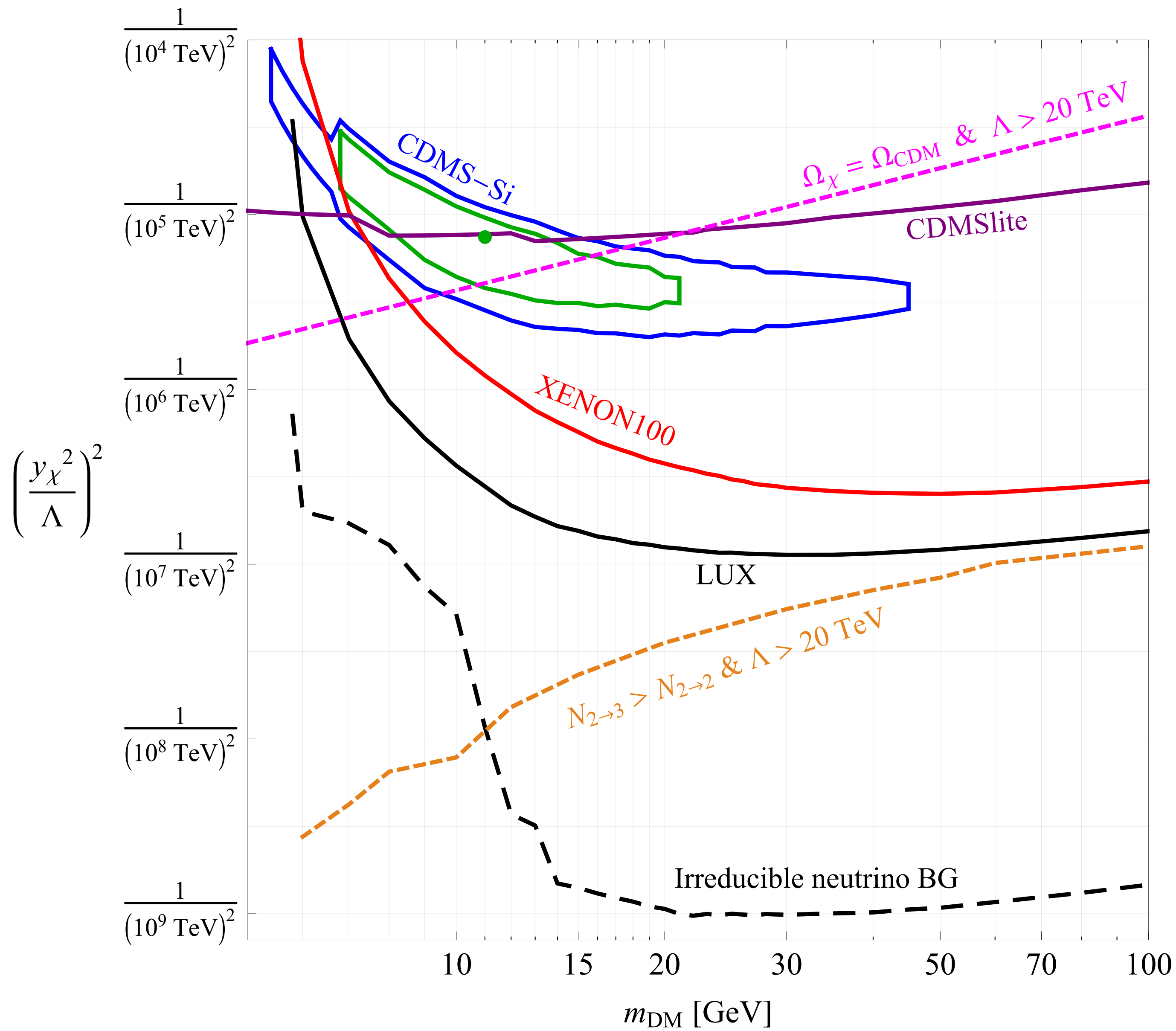
Loop-induced 2 to 2 process

The simplest model generates a 2 to 2 scattering



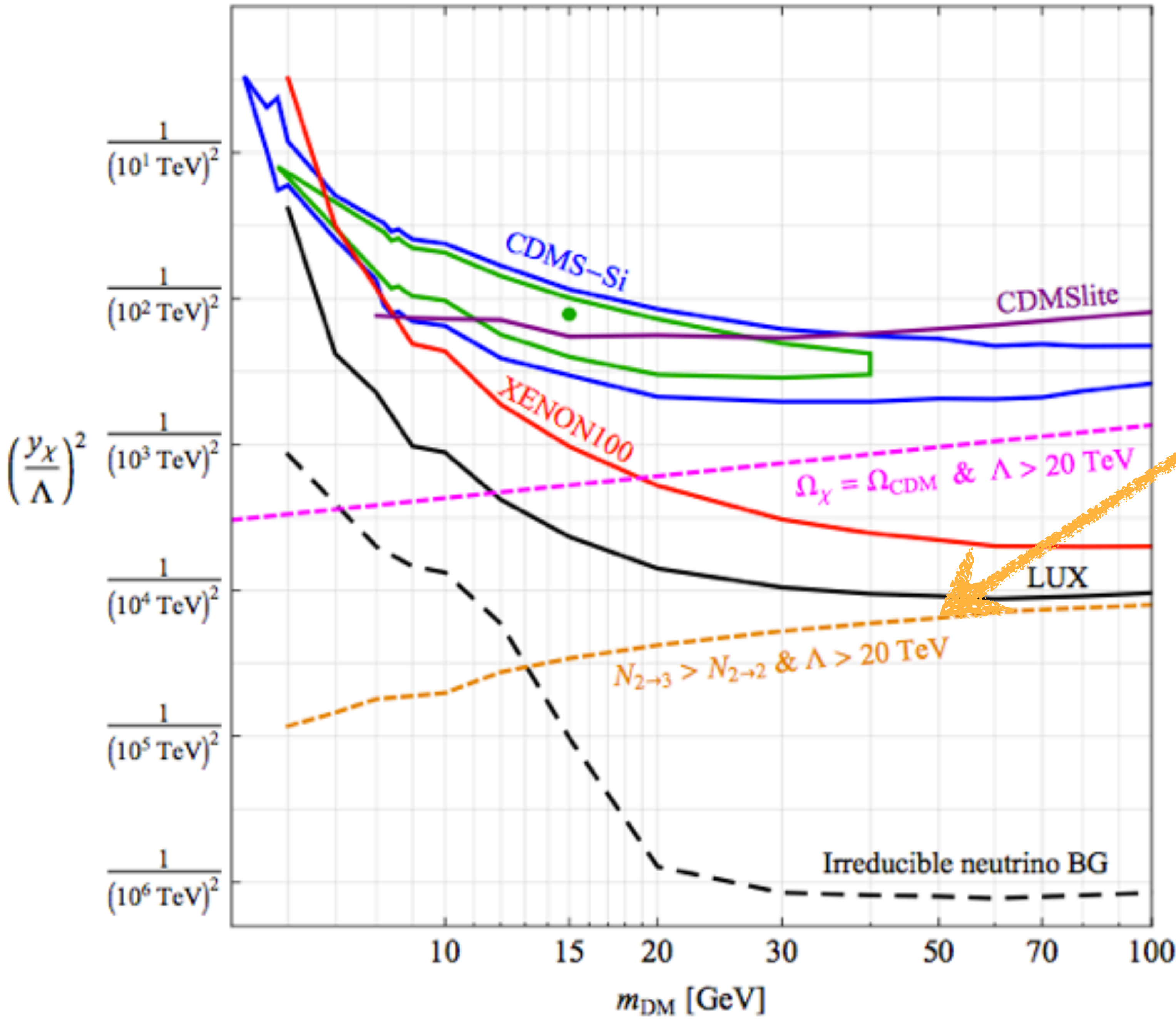
$$\approx \frac{y_\chi^2}{2\pi^2}\frac{1}{\Lambda q}(\bar{\chi}\chi\bar{N}N)$$

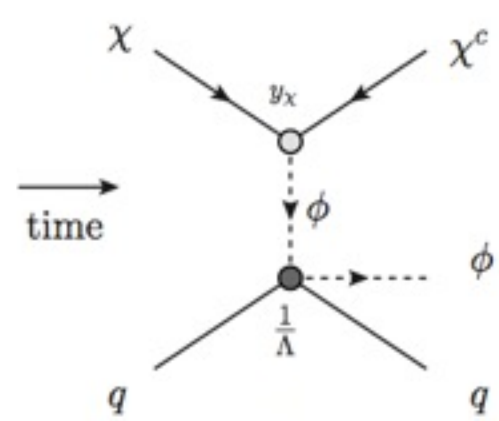
$$q = \sqrt{2\, m_N\, E_R}$$



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

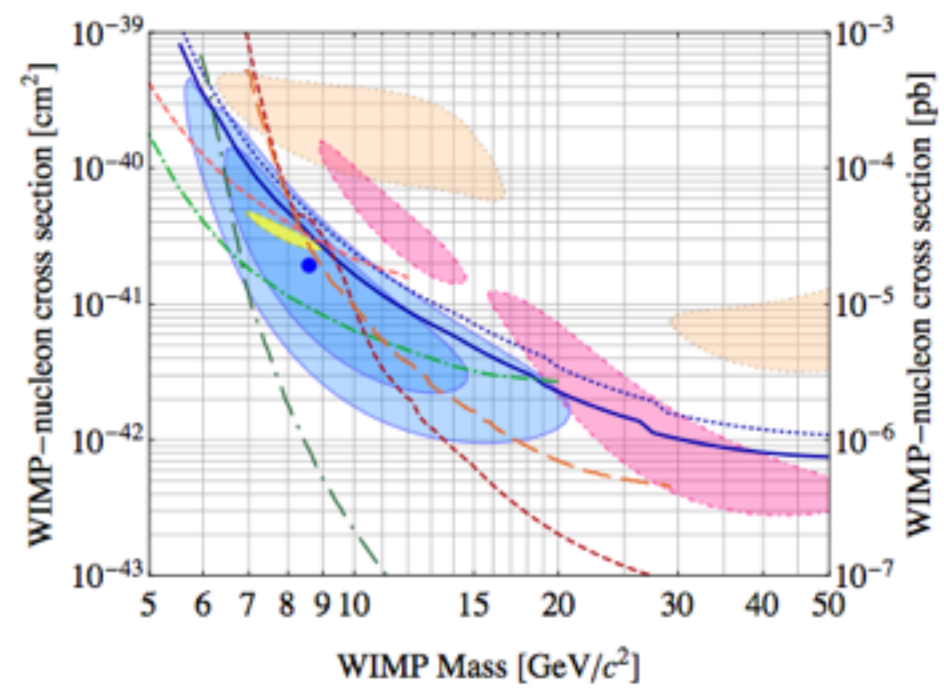
Interaction vs. mass





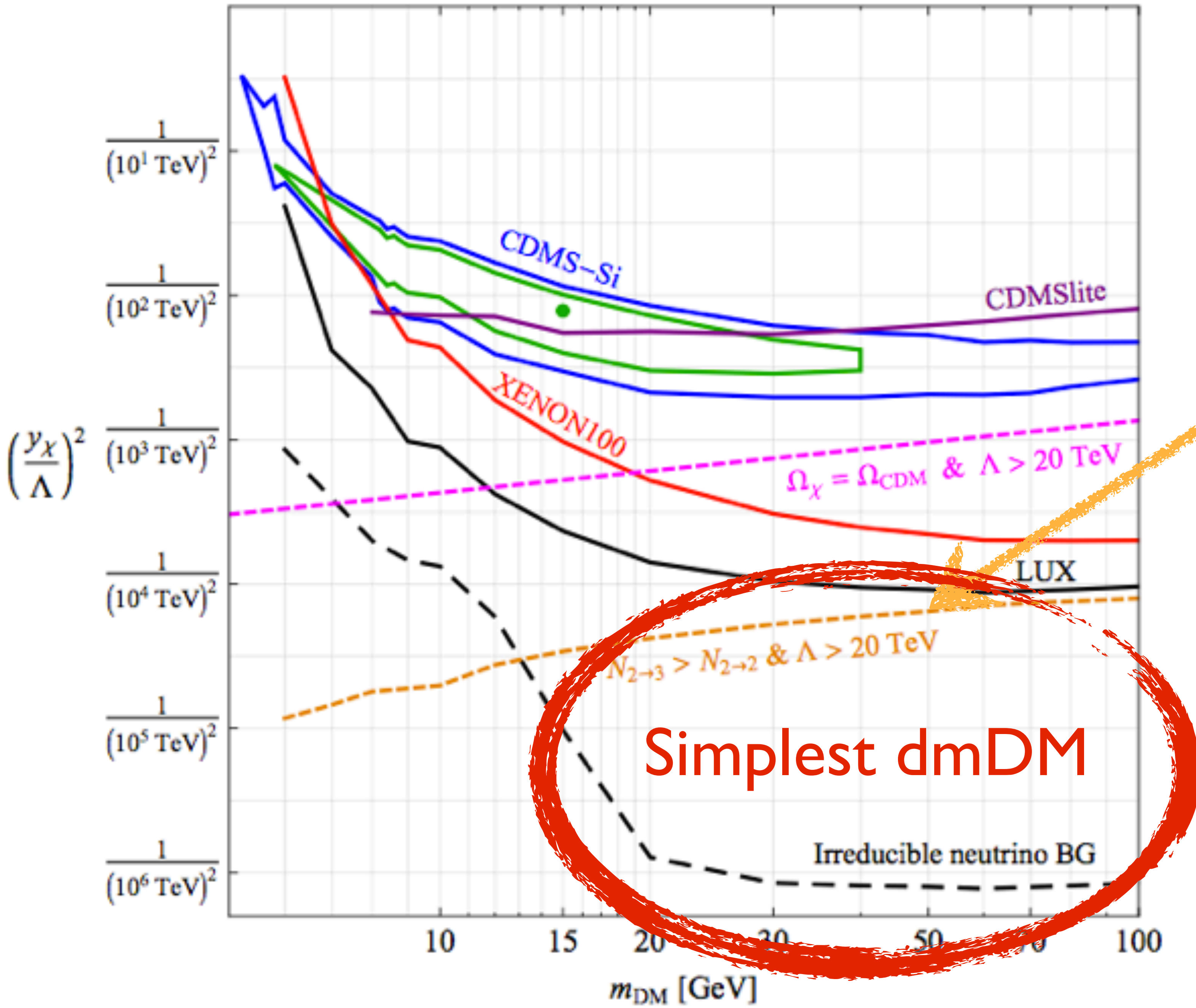
$$\sigma \propto \left|\frac{y_\chi}{\Lambda}\right|^2$$

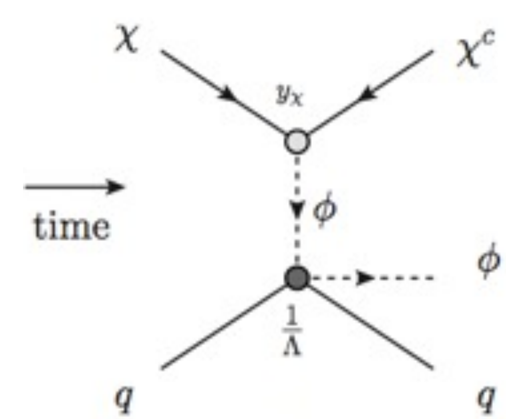
for 2 to 3 > 2 to 2 $\Lambda > 20\,\mathrm{TeV}$ is given by the cooling constraints



Monday, February 10, 2014

Interaction vs. mass





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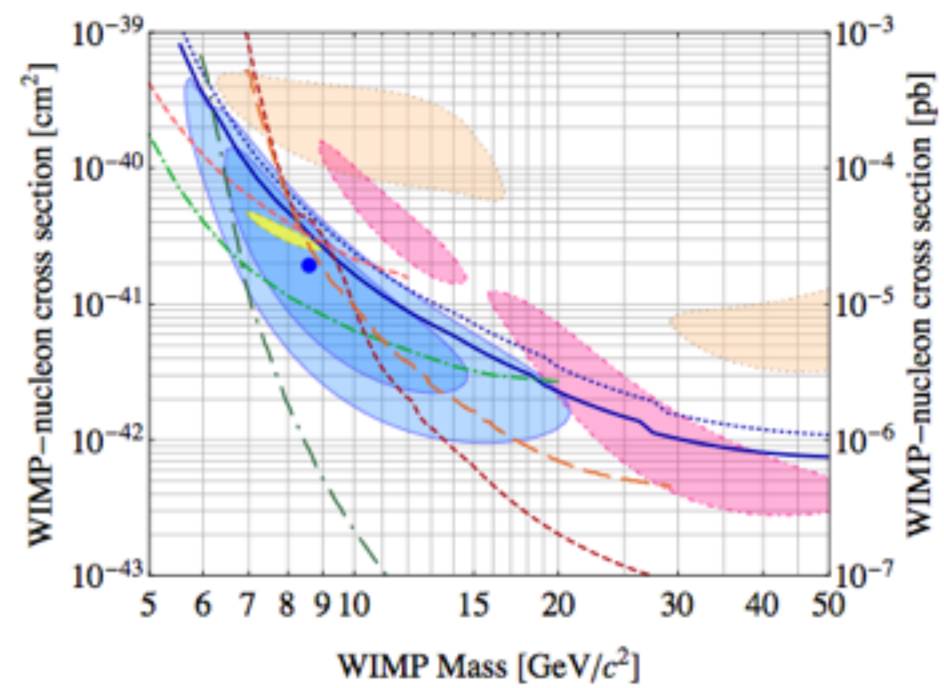
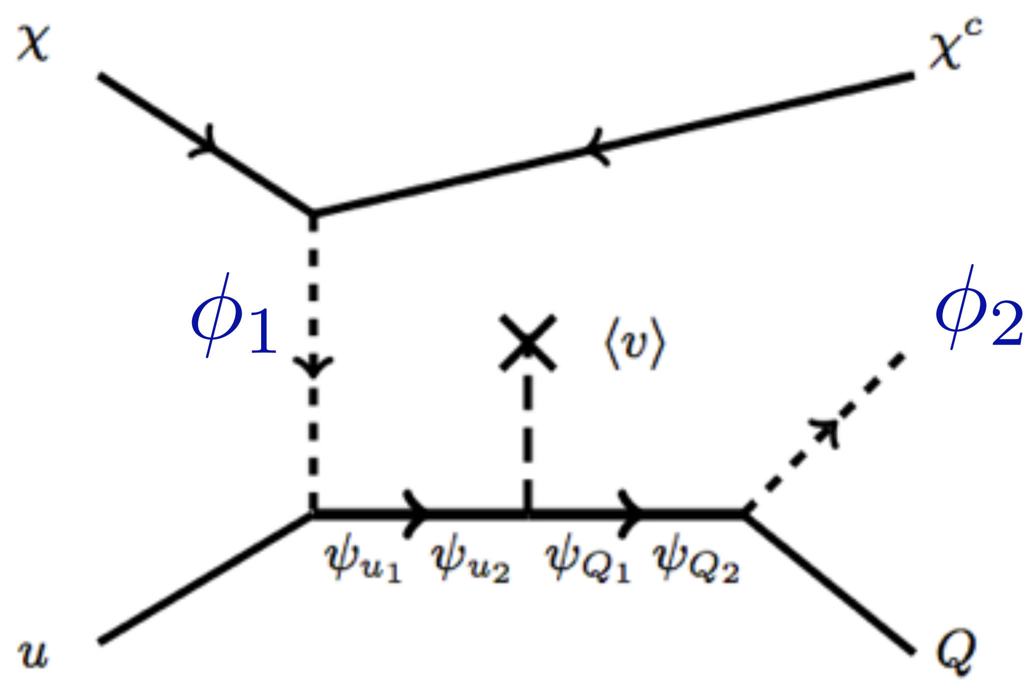
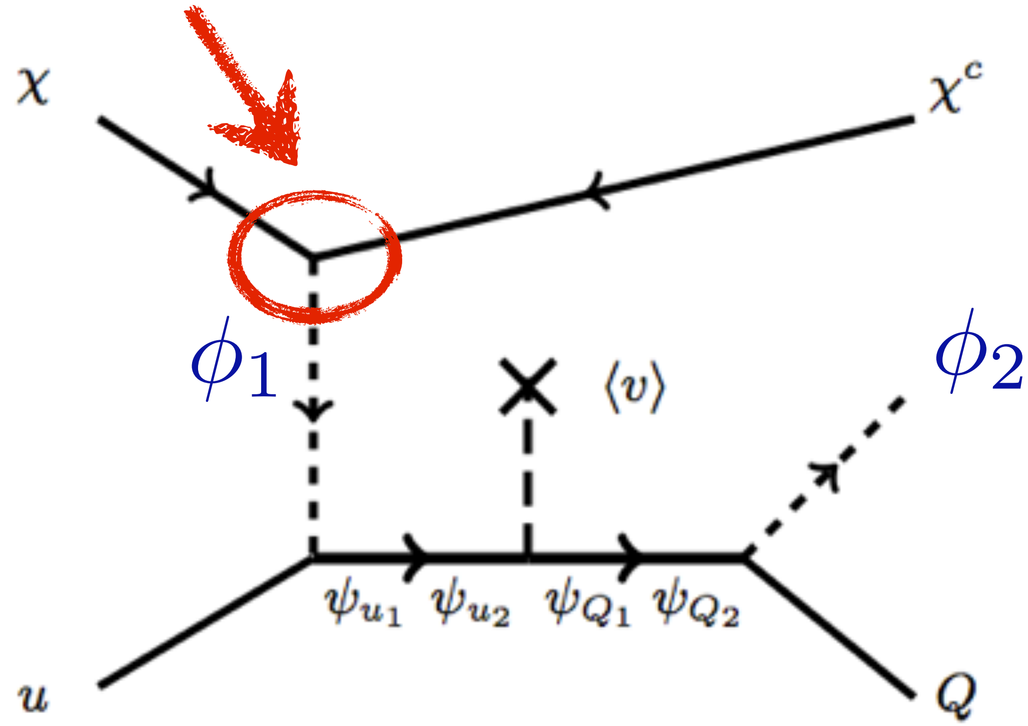


Various Constraints on dmDM



Various Constraints on dmDM

DM self-interaction bounds
DM relic abundance Ω_X



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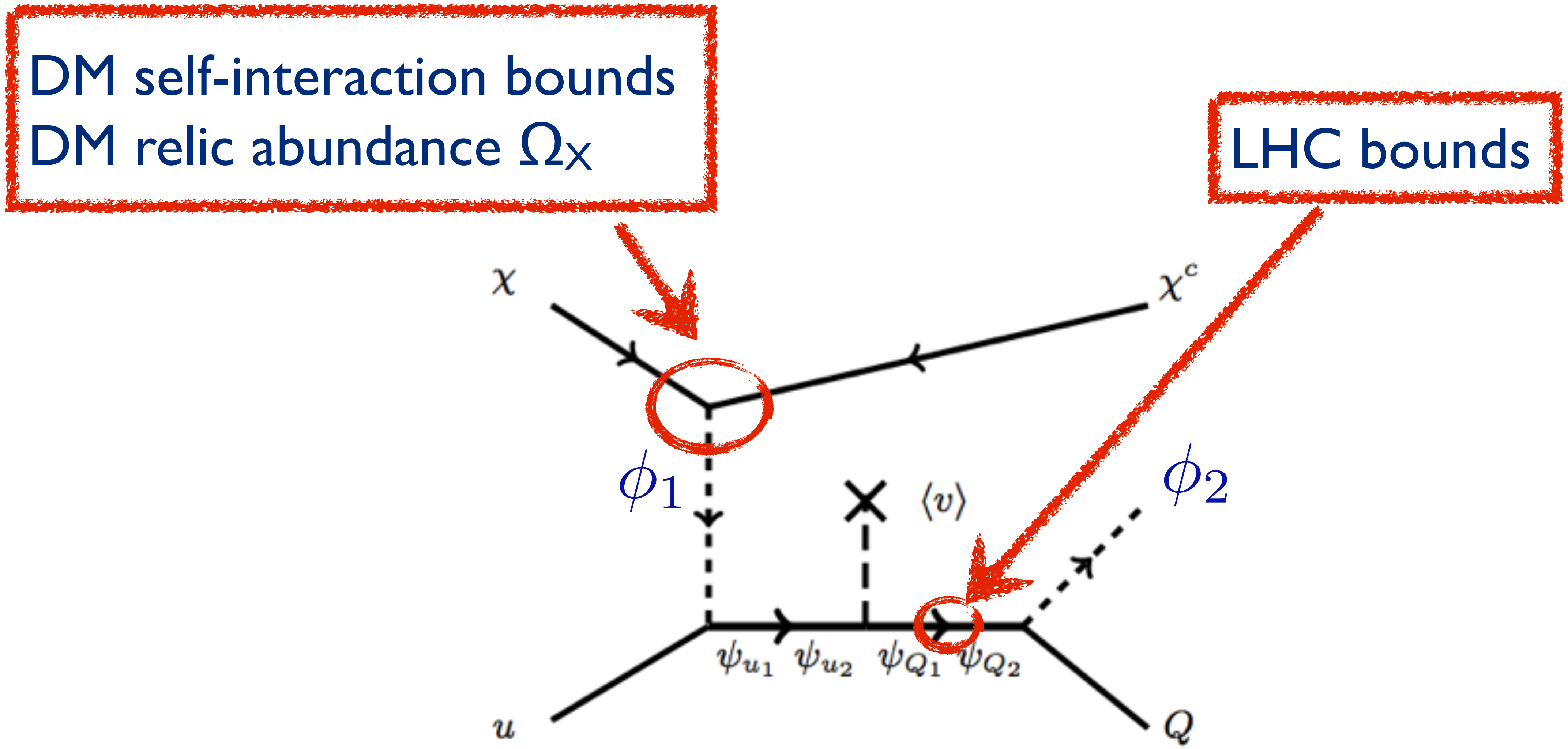
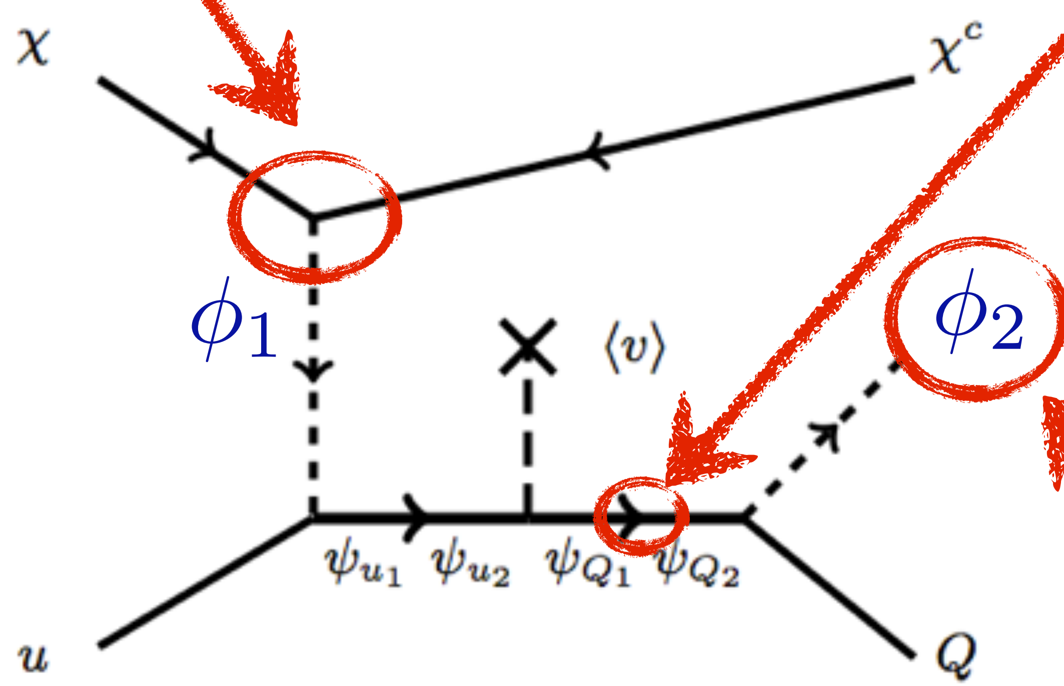


Various Constraints on dmDM

DM self-interaction bounds
DM relic abundance Ω_χ

LHC bounds

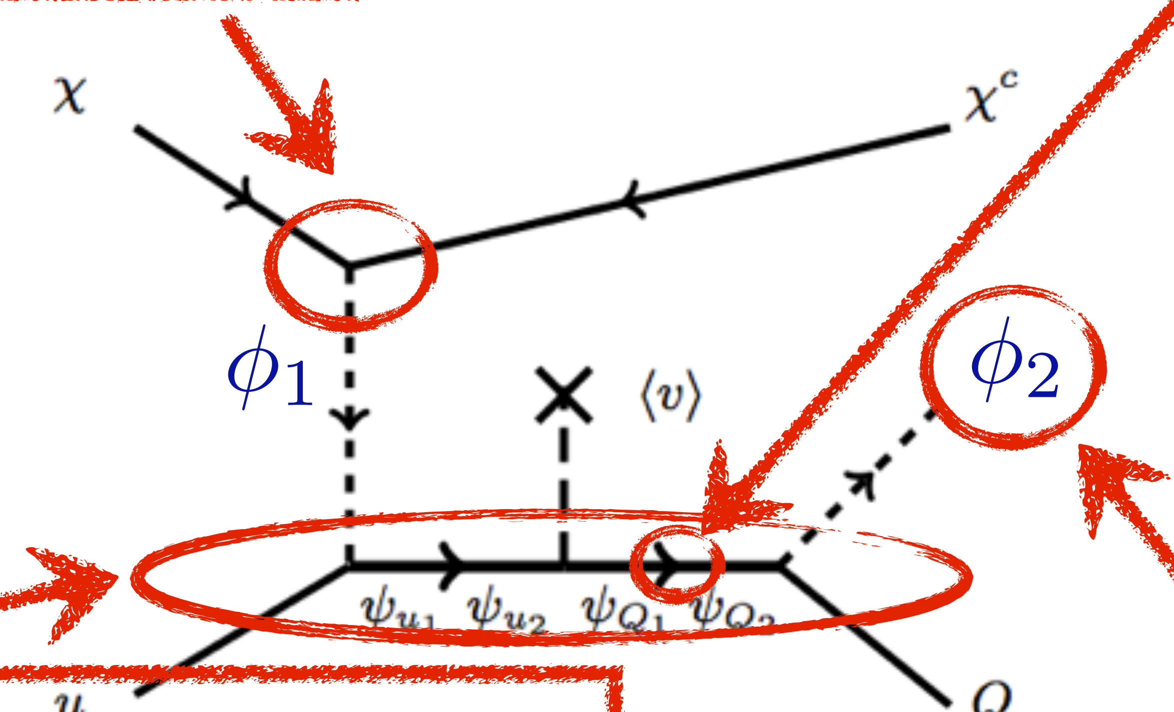


Ω_ϕ
BBN: N_{eff}
Structure Formation

Various Constraints on dmDM

DM self-interaction bounds
DM relic abundance Ω_X

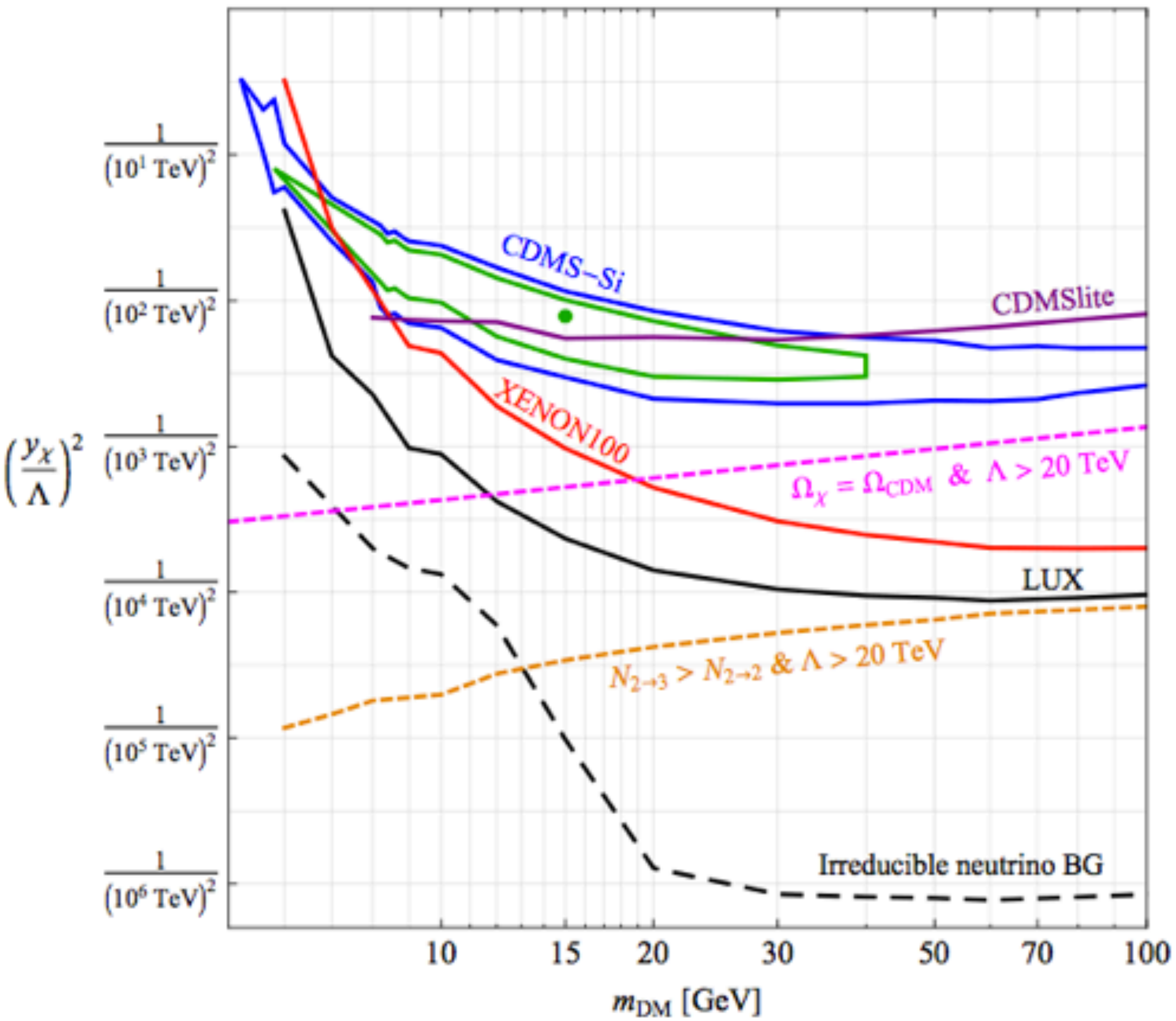
LHC bounds



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

Ω_ϕ
BBN: N_{eff}
Structure Formation

Various Constraints on dmDM



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

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

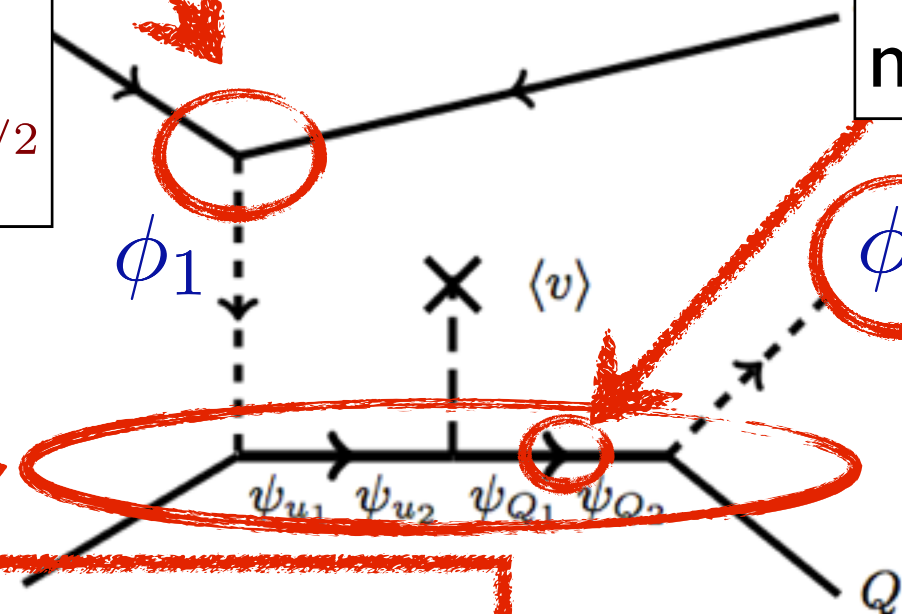
Various Constraints on dmDM

DM self-interaction bounds
DM relic abundance Ω_χ

LHC bounds

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

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



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Λ bounds are weaker than 10 TeV

Ω_ϕ
BBN: N_{eff}
Structure Formation

Cosmological Constraints : Neff

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

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

This can be relaxed when having ϕ as a real scalar charged under a Z4 symmetry $\phi \to -\phi,\, \chi \to e^{i\pi/2}\chi$ so the deviation becomes small

Ω_ϕ & the structure formation

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

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

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

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

ϕ satisfies similar constraints as a light sterile neutrino

- Can also make ϕ 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 $X_1\ X_2 \rightarrow \phi + \ldots$ yields $r_\phi = n_{X1}\, n_{X2}\, c\, \sigma_{\phi prod}$ ϕs per unit volume per unit time.
- If we know the radial profiles of stellar density, temperature and composition we can find the total ϕ production rate for the star *(assuming ϕ does not significantly alter stellar evolution)*.
- In the absence of significant ϕ-destroying processes, this is equal to the equillibrium total ϕ loss rate.

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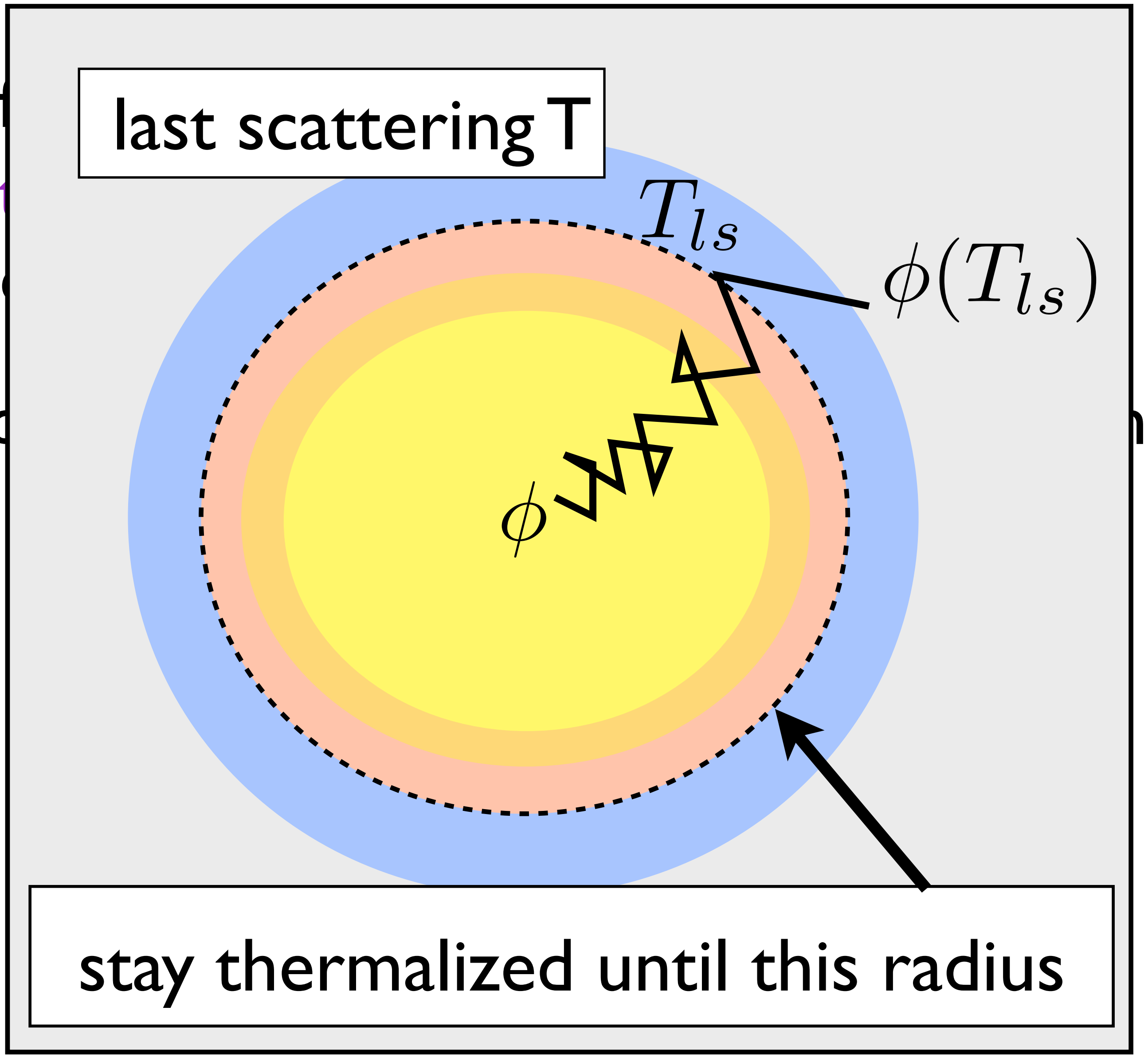
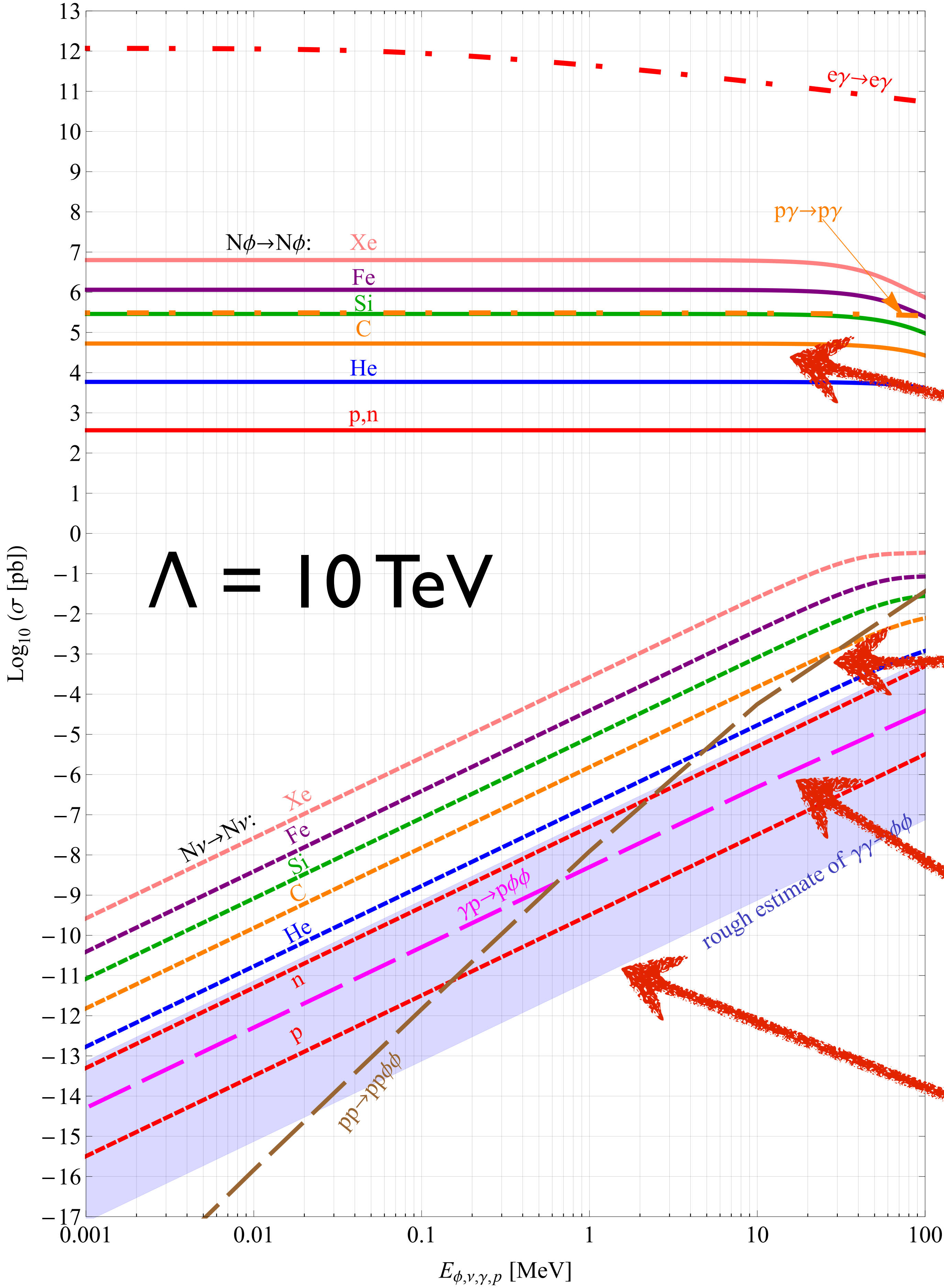
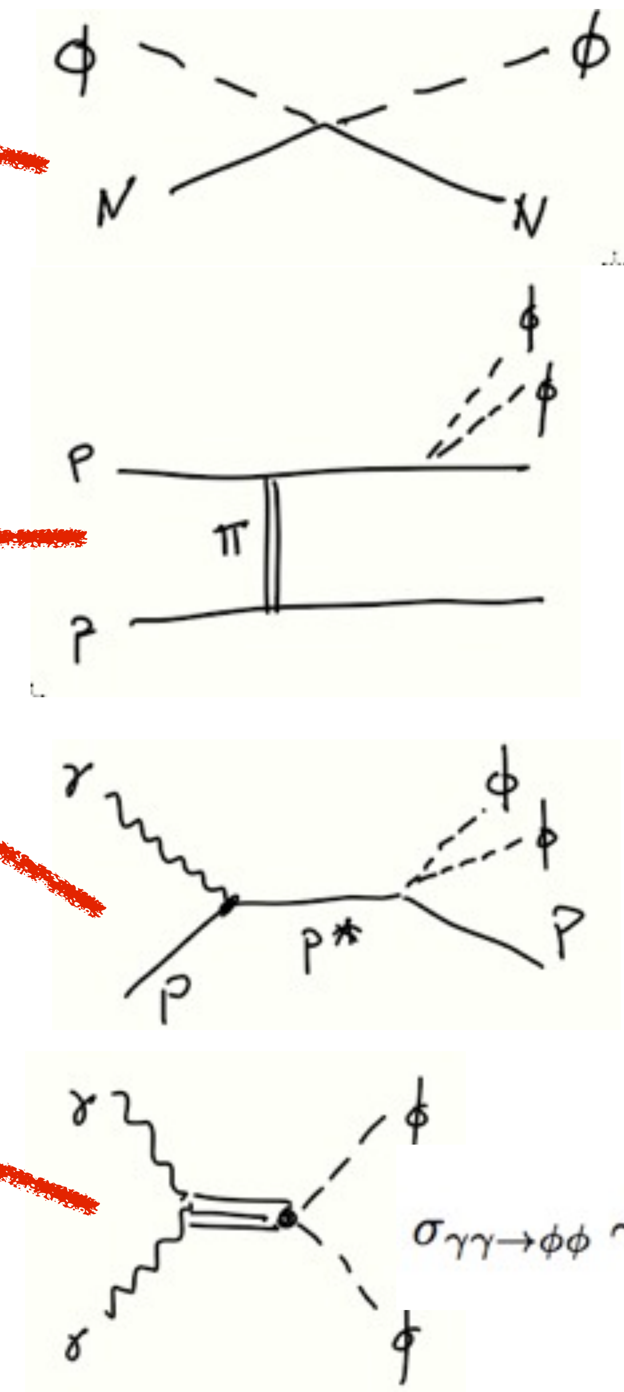


This allows us to compute the energy lost due to ϕ emission.

Compute ϕ low-energy scattering and production cross sections analytically and in MadGraph.





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

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

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

The Sun

- Core temperature is about T ~ 1 keV
- The most important ϕ production process is γ N → N ϕ ϕ
- For Λ = 10 TeV, ϕ decouples at r ~ 0.7 x R_{sun} where T ~ 0.1 keV

  solar ϕ luminosity < 1% photon luminosity requires Λ > 1 TeV.
- Need the "heat transfer" of ϕ to be much smaller than the photon's

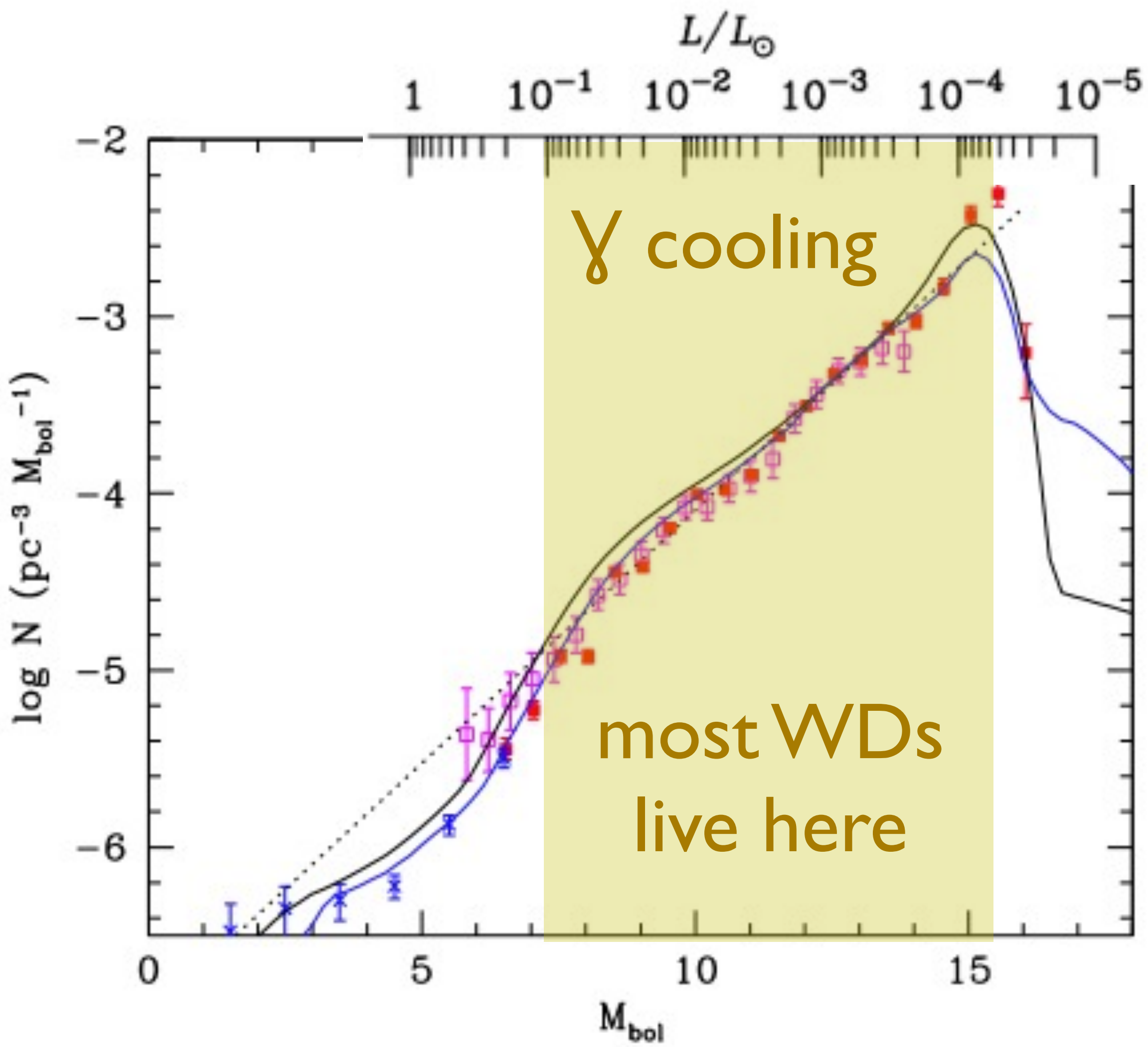
$$\frac{F_\phi}{F_\gamma} \sim \frac{n_\phi L_\phi}{n_\gamma L_\gamma} \ll 1$$

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

No significant constraint

White Dwarfs

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



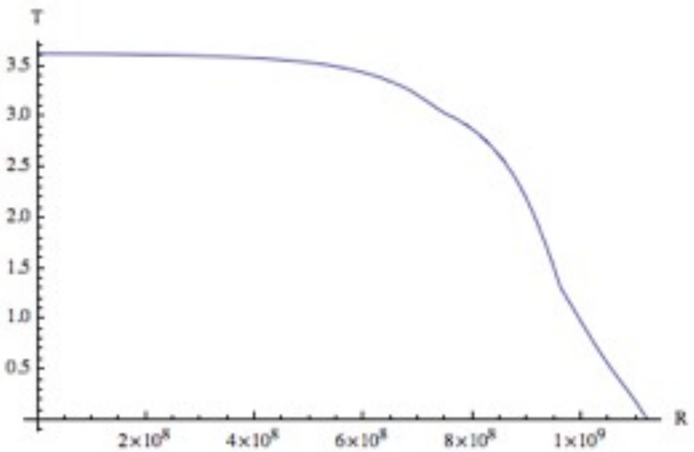
Dreiner, Fortin, Isern, Ubaldi (13')

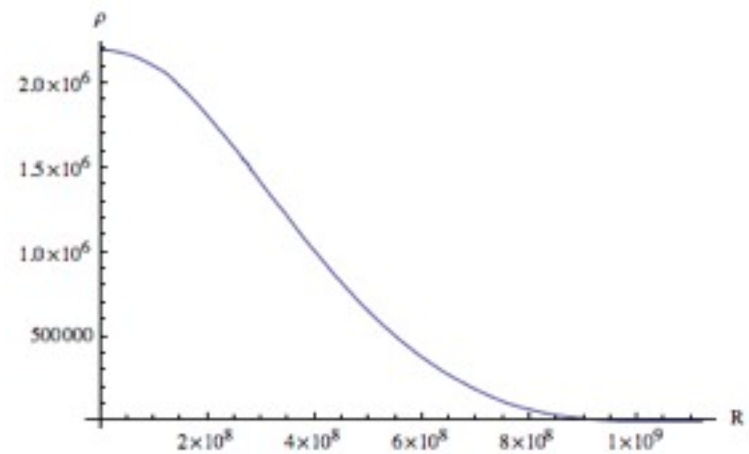
Observational data in good agreement with standard cooling theory!

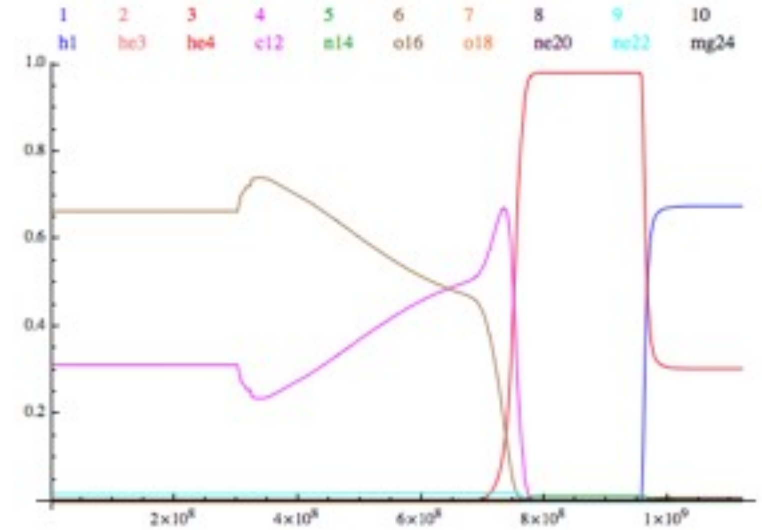
Need the scalar cooling to be much smaller than the photon cooling.

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").





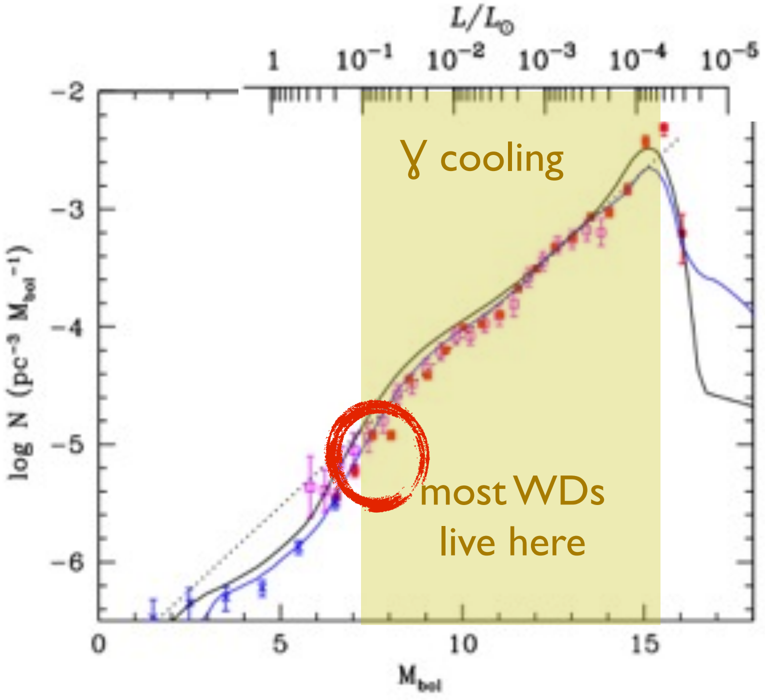


When our test dwarf has 0.1 x solar luminosity (very

ϕ power output is < 10% total WD luminosity if

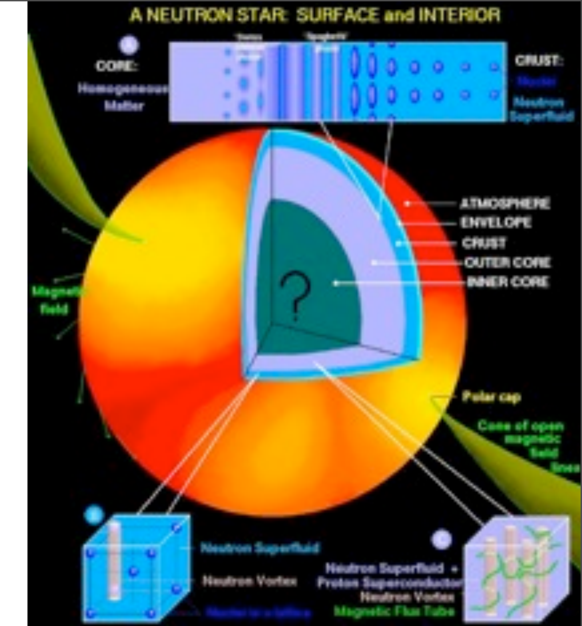
$$\Lambda > 20\ \mathrm{TeV}$$

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



(ϕ emission even less important at lower core temperature)

Neutron Stars

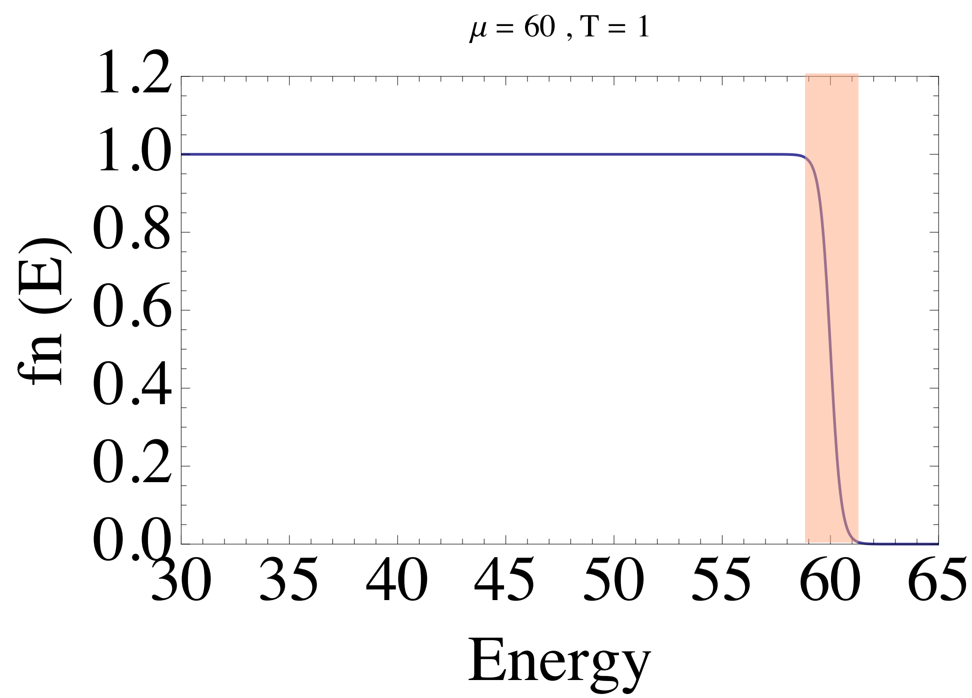


Lots of ϕ production in neutron star core via

$$n\,n \rightarrow n\,n\,\phi\,\phi$$

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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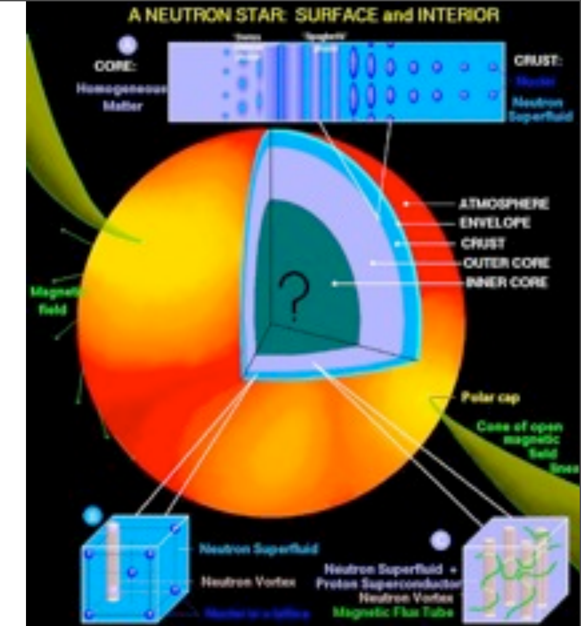

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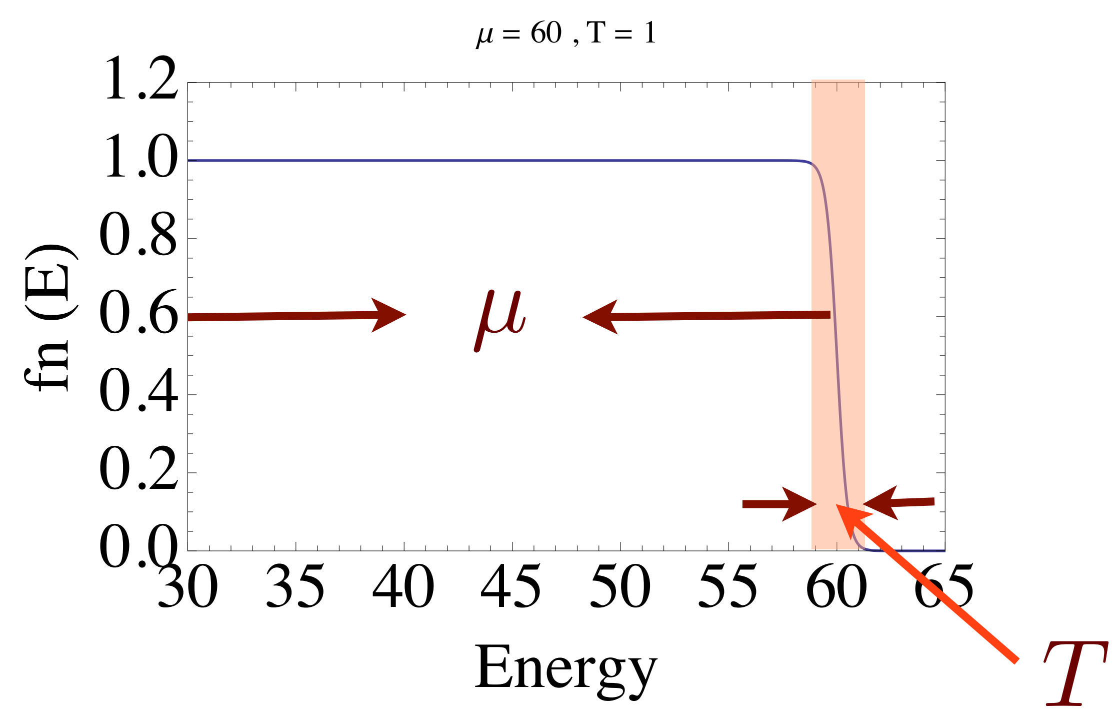


The neutrons scattering then is suppressed by a factor

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

which gives a small production rate

No significant constraint

Supernovae

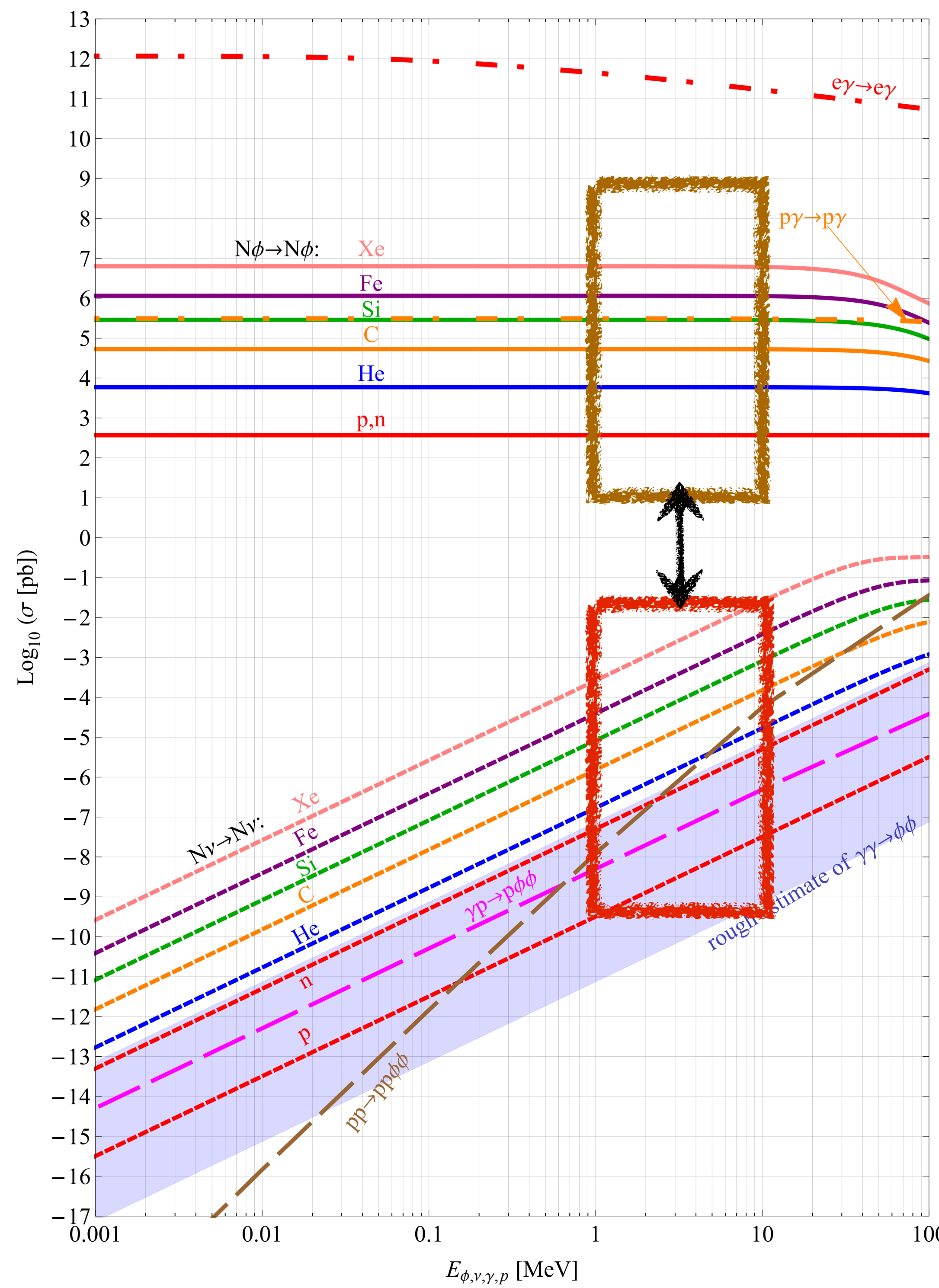
$$\frac{\phi^* \phi \, \bar{Q} q}{\Lambda} \quad \Rightarrow \sigma_{N\,\phi} \propto \frac{1}{\Lambda^2}$$

while $$\sigma_{N\,\nu} \propto \frac{T^2}{m_W^4}$$

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

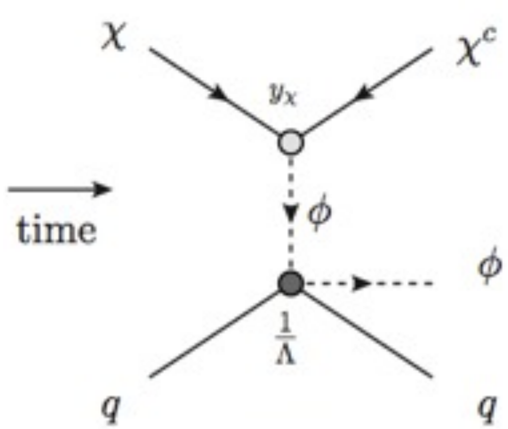
$$\Lambda \lesssim 10^6 \text{ TeV}$$

Gives an upper bound

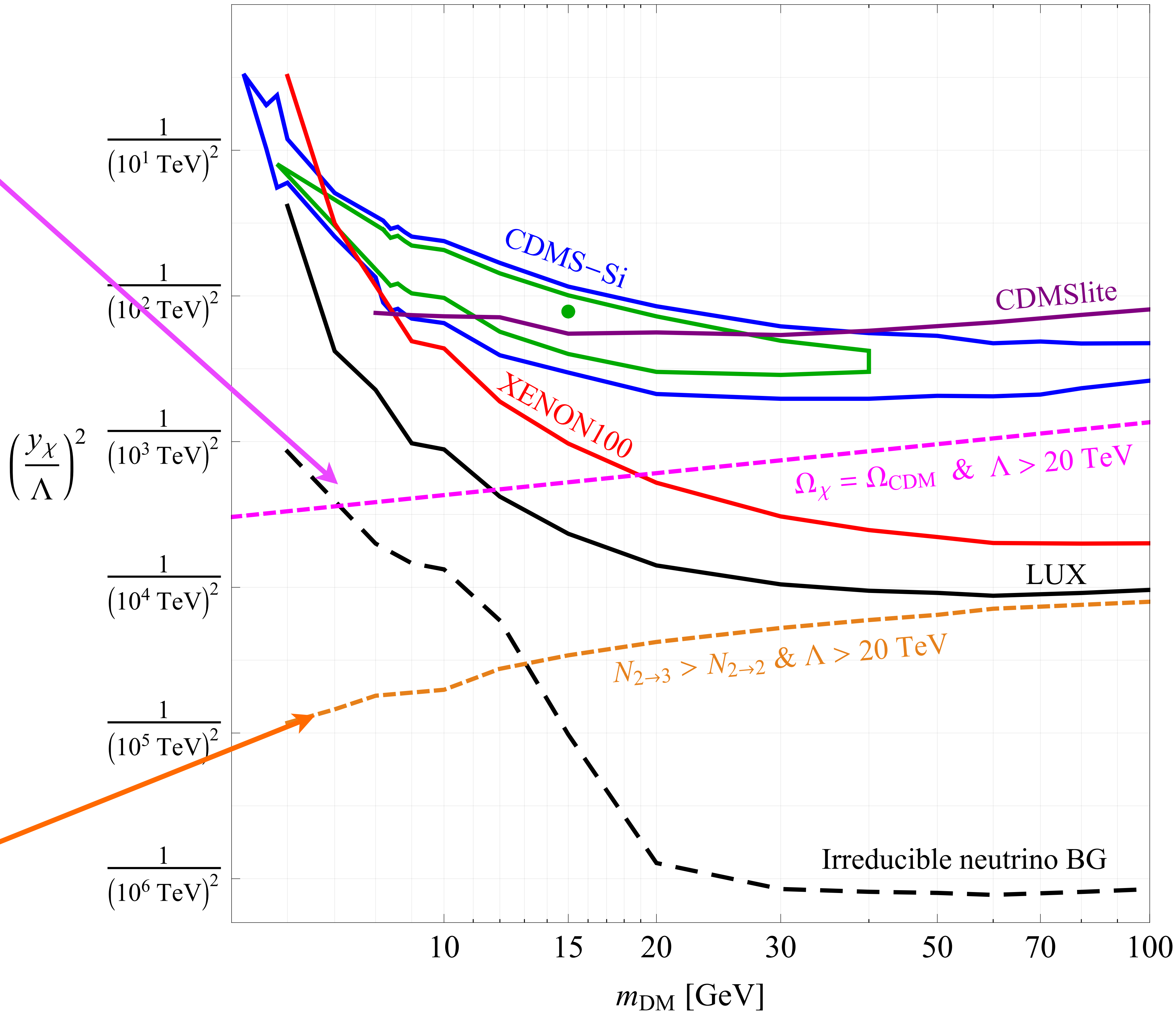


Bound on the dmDM model

Λ > 20 Tev
and
y_χ correct value for DM relic density

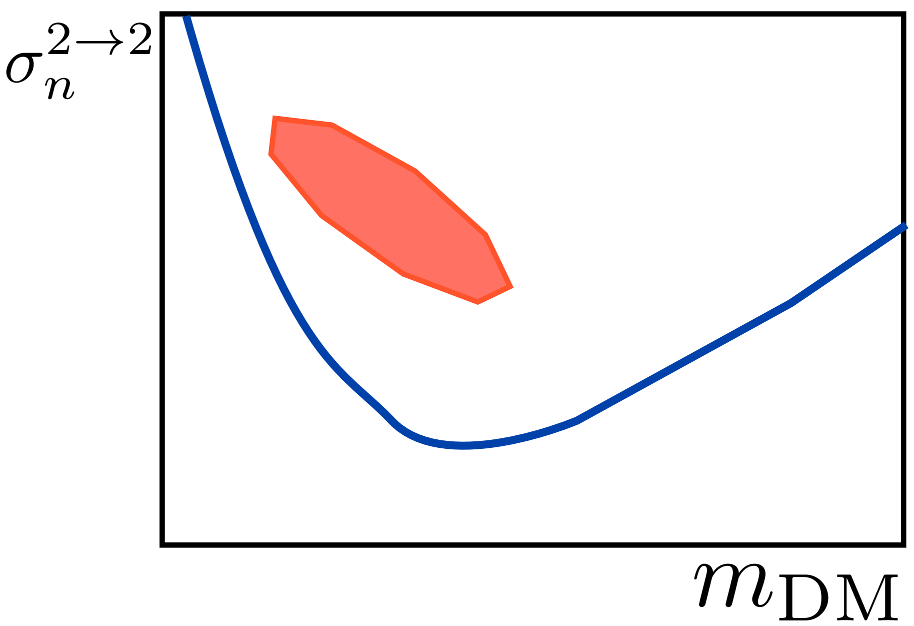


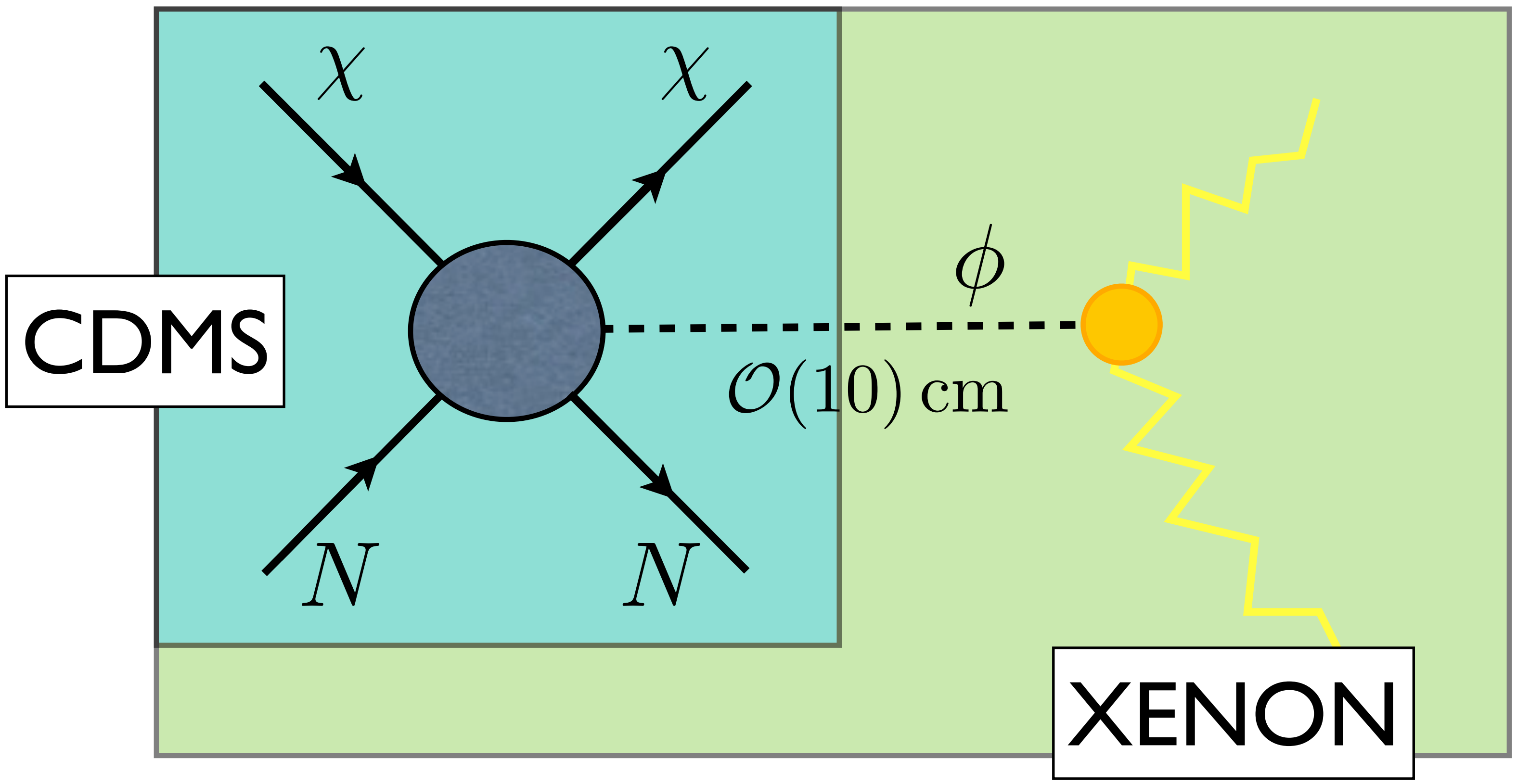
Λ > 20 Tev
and
y_χ small enough to ensure subdominant $2 \to 2$



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 $\Lambda < \rm GeV$ unless the DM velocity is large (~ 0.01) so the Λ can be of TeV scale

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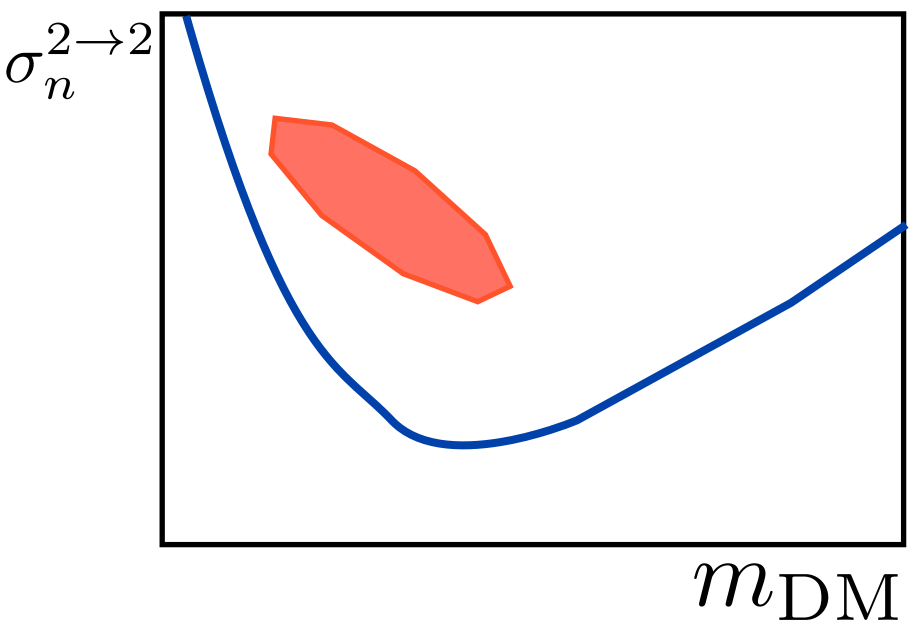

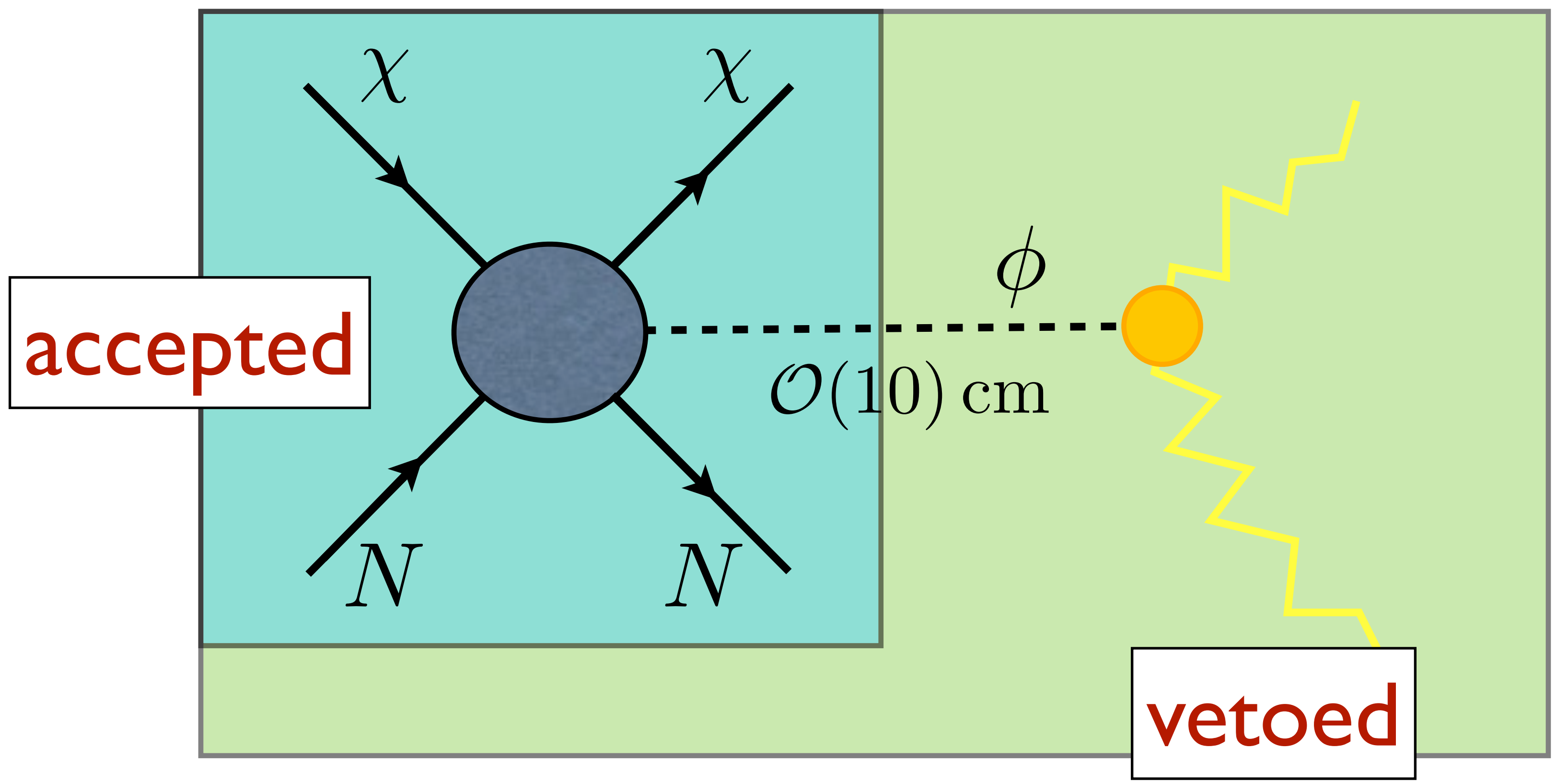

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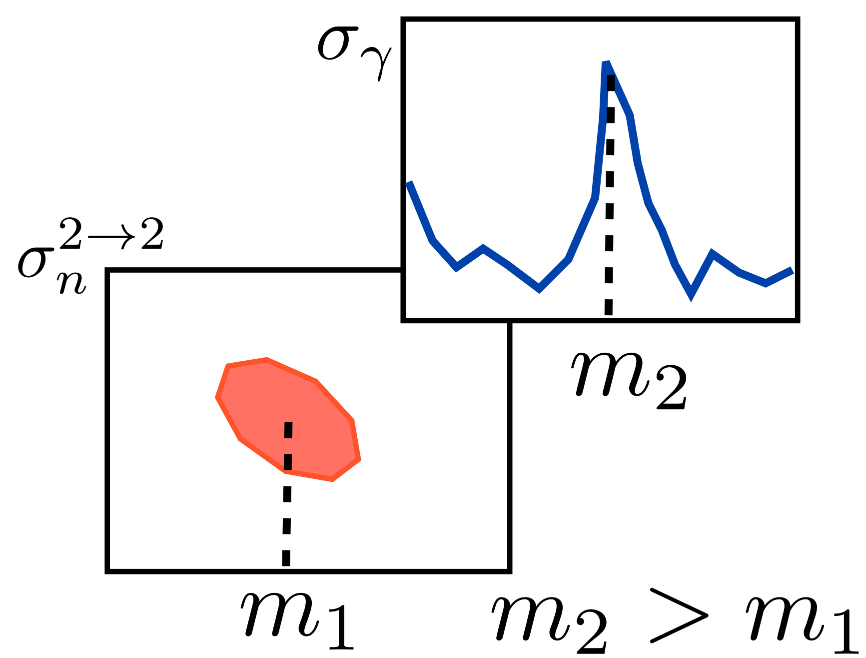
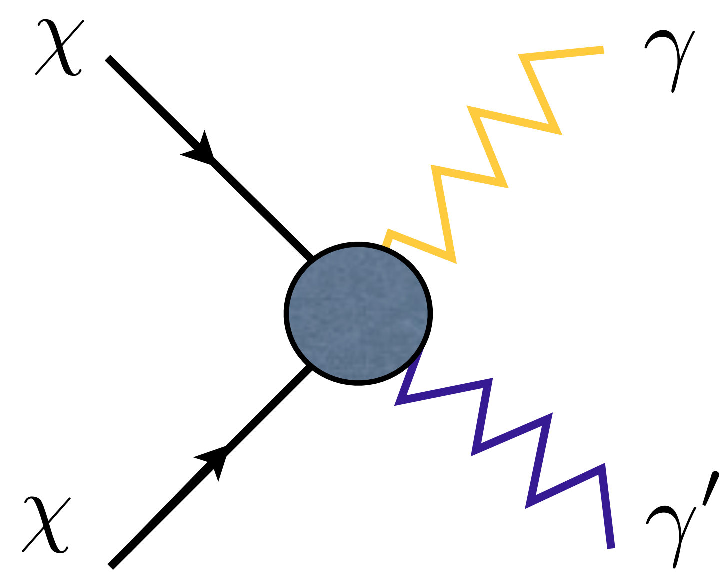
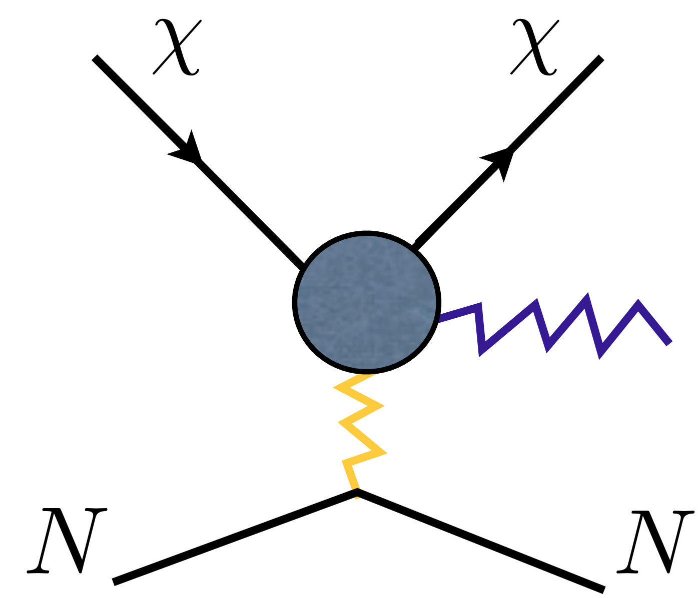
Other "possible" uses

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 σ_n too small 

Conclusion

dmDM is the first DM model featuring 2→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.

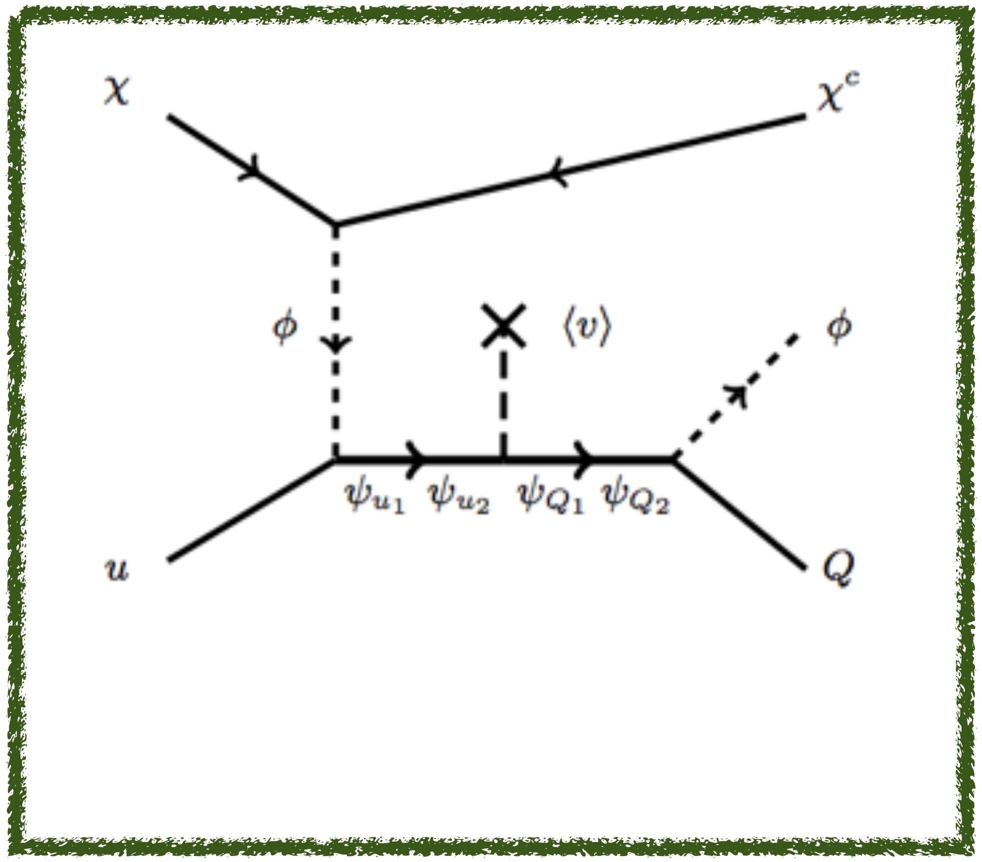
Cosmo + Astro sets significant constraints, but large regions of detectable parameter space remain. The bound can be relaxed by the **heavy**light setup.

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



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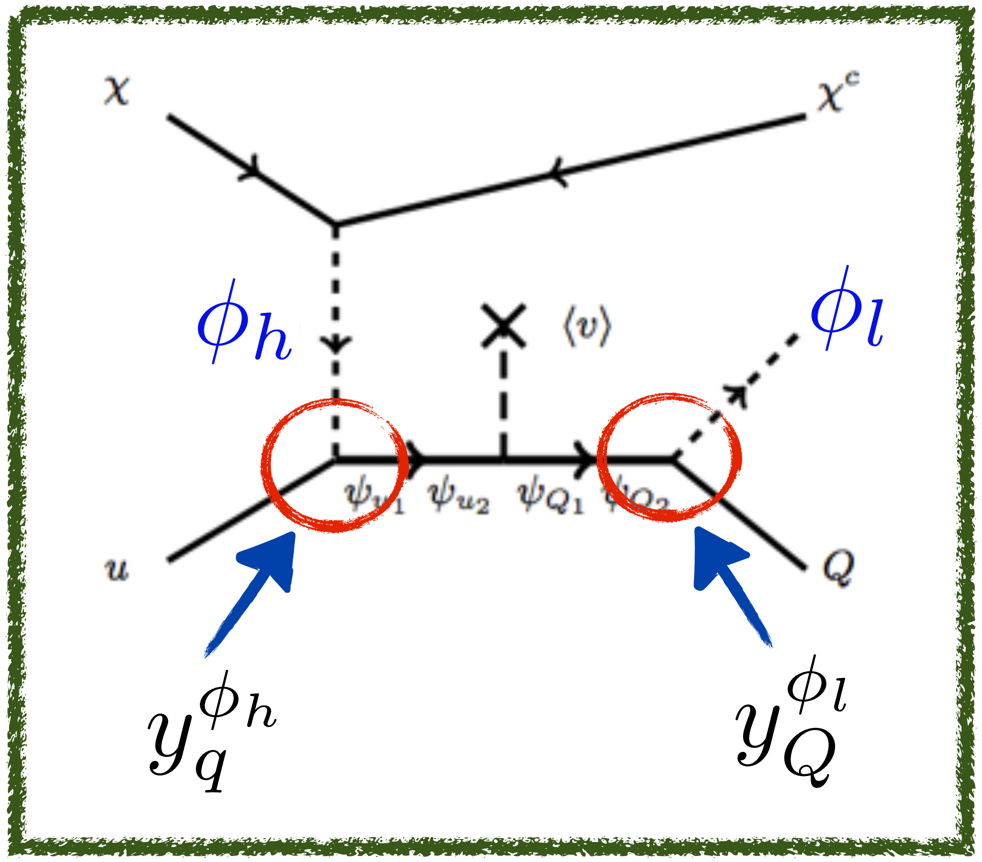
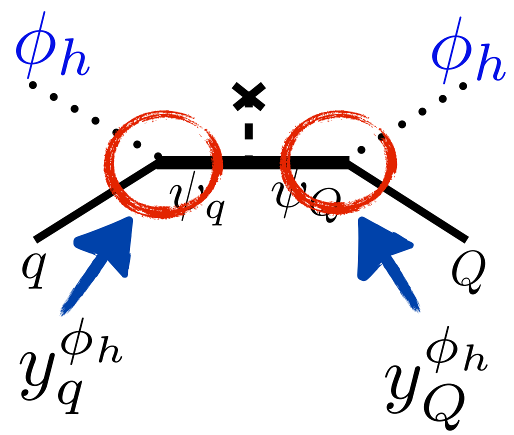


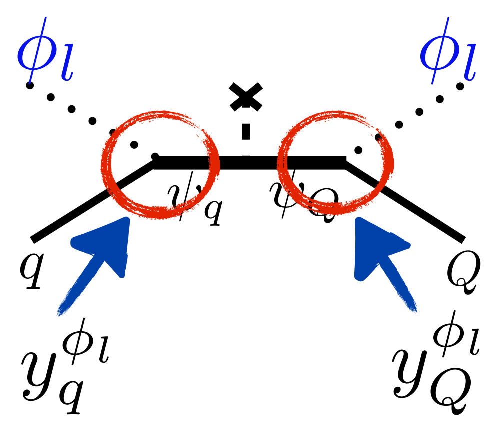
heavylight model with

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

to avoid the sizable stellar production of ϕ

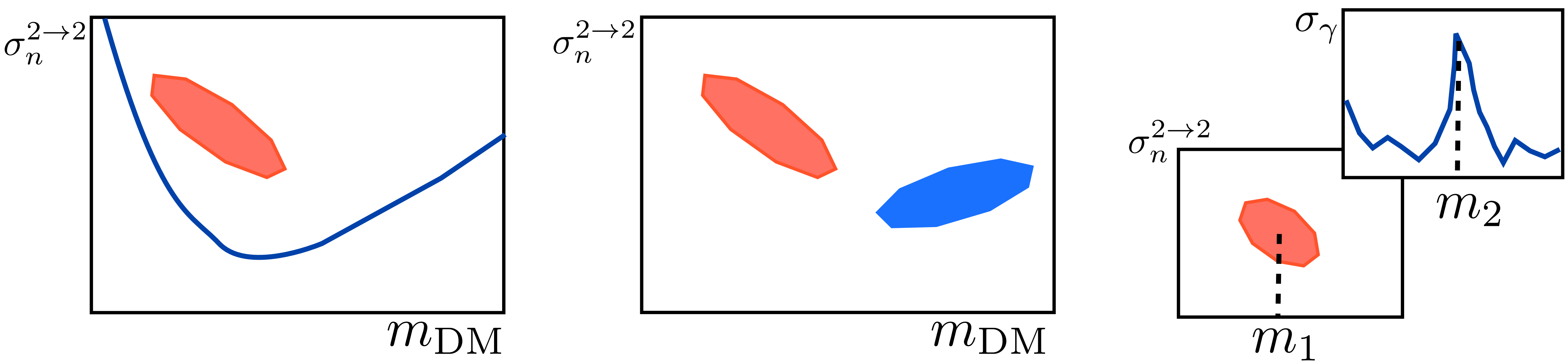
Moreover, if $y_{\chi\,\phi_l},\ y_Q^{\phi_h} < 10^{-3}$,
the loop-induced 2 to 2 process will be < 10% of the 2 to 3 while keeping the $\sigma_{2\to 3}$ large





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

Other possible use of 2to3



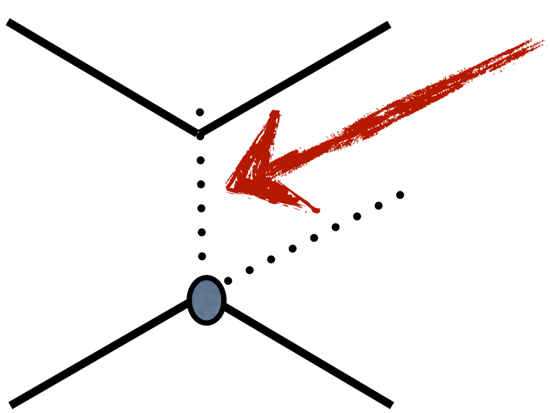
$E, |\vec{p}|$ in a non-relativistic scattering

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

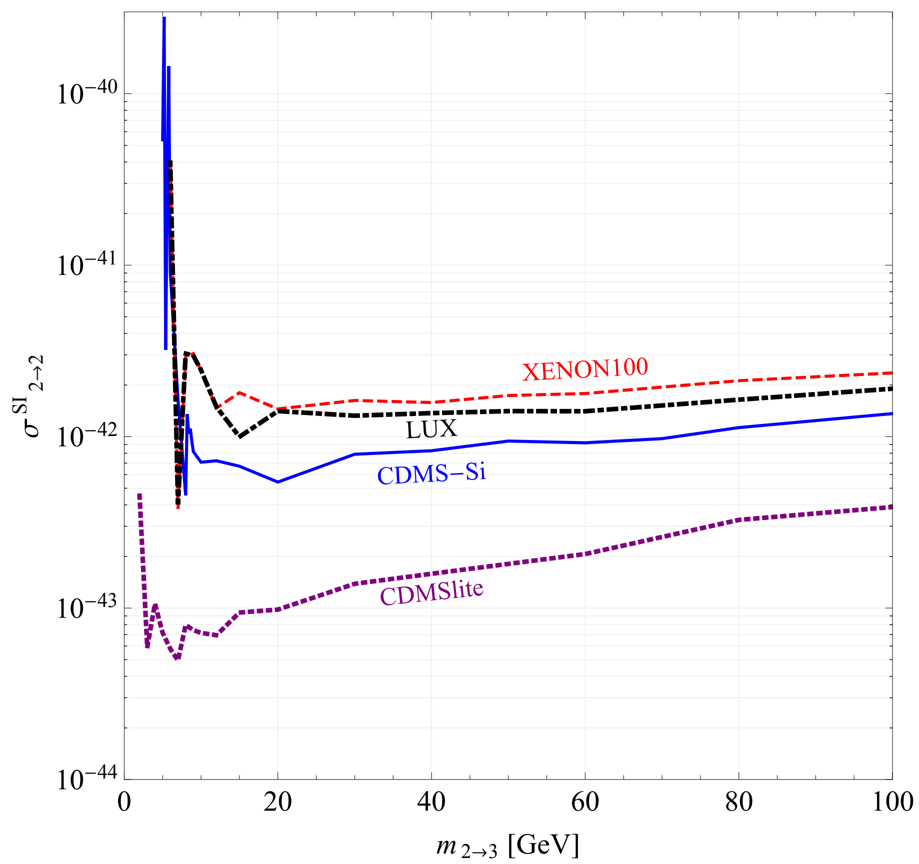
$$|\vec{p}_\phi| \simeq E^\phi < E_k^\chi \ll |\vec{p}_{\chi,\,N}|$$

ϕ carries away sizable energy but not much momentum!

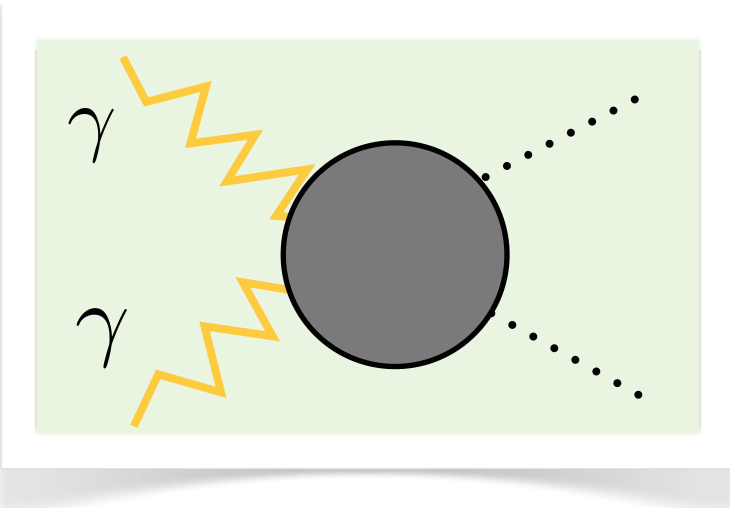


$$(\Delta p_N + p_\phi)^{-4} \simeq (\Delta p_N^2 + 2 p_\phi \cdot \Delta p_N)^{-2}$$
$$\simeq (|\vec{p}_N|^2 + 2|\vec{p}_\phi||\vec{p}_N|)^{-2}$$
$$\simeq (2 m_N\, E_R)^{-2}$$

Interaction strength



Cosmological Constraints : Neff



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

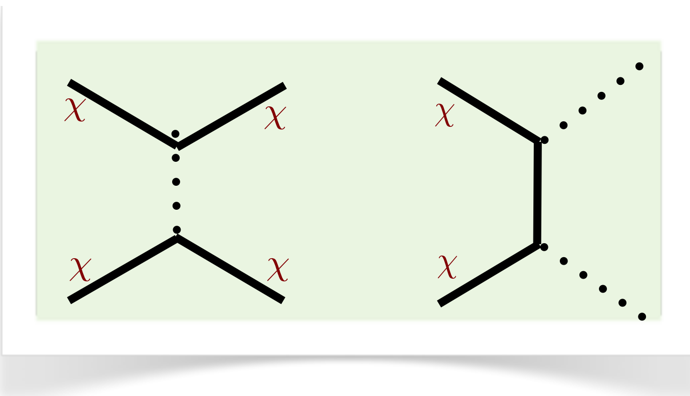
$$\sigma_{\gamma\gamma\to\phi\phi} \sim \frac{1}{16\,\pi}\left(\frac{\alpha}{\pi\, m_q}\right)^2 \left(\frac{\mathcal{B}}{\Lambda}\right)^2 E_\gamma^2 \qquad \mathcal{B}^2 = 1 - 100$$

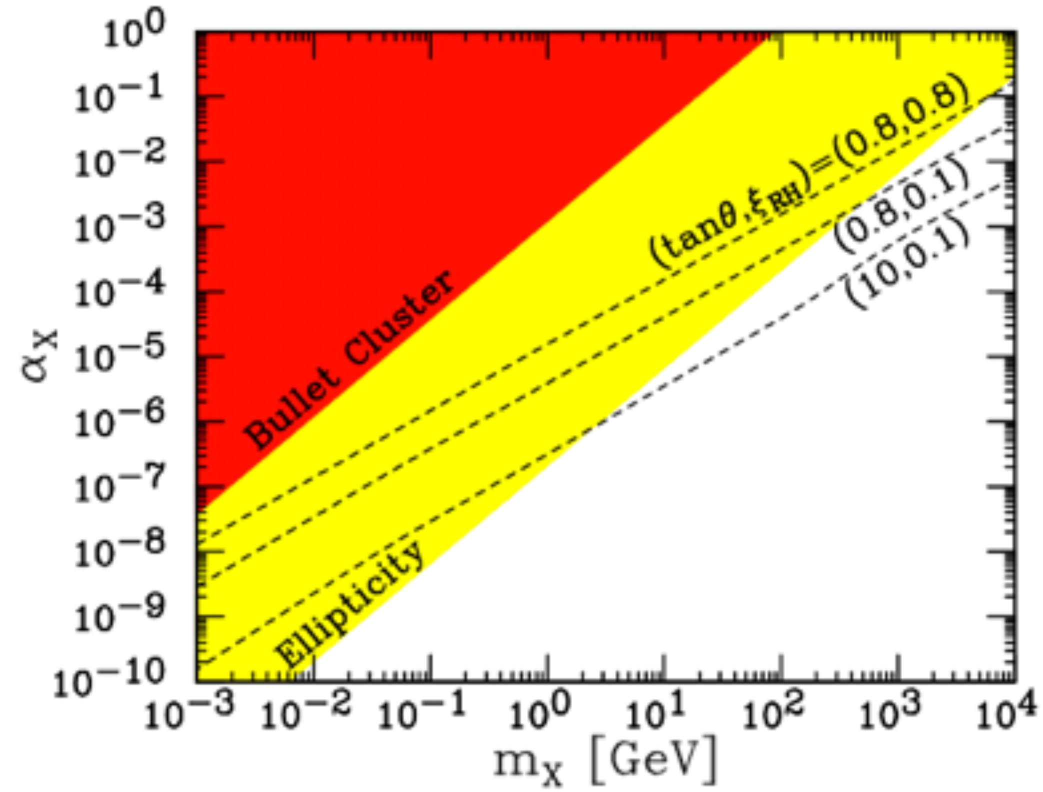
ϕ decoupled from thermal bath at $T_\phi^{freeze} > 10\,\mathrm{MeV}\left(\frac{\Lambda}{10\,\mathrm{TeV}}\right)^{2/3}$

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

This can be relaxed when having ϕ as a real scalar charged under a Z4 symmetry $\phi \to -\phi,\ \chi \to e^{i\pi/2}\chi$

Constraints on the dark coupling



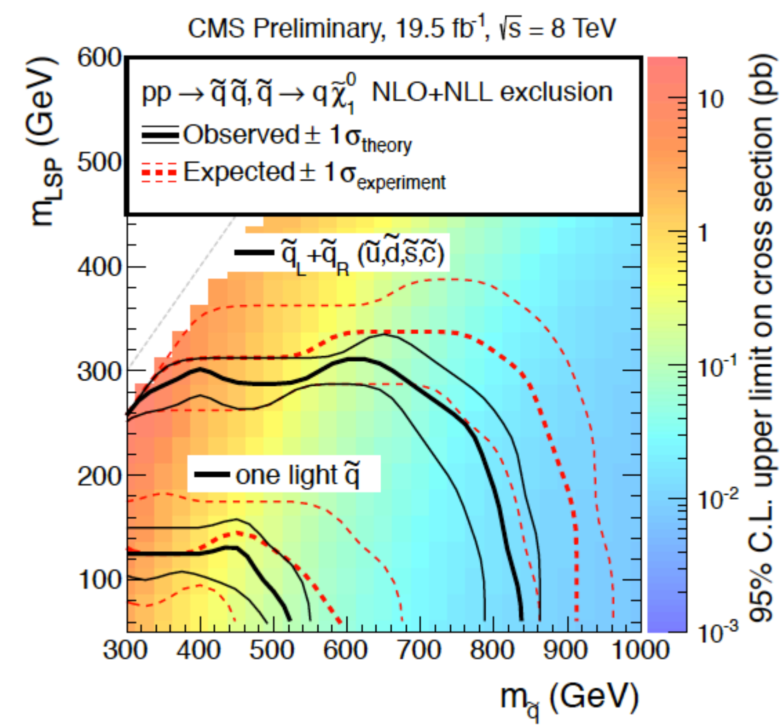


Jonathan L. Feng, Manoj Kaplinghat, Huitzu Tu, and Hai-Bo Yu (09)

- 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 $y_\chi \approx 2.7 \times 10^{-3} (m_\chi/\mathrm{GeV})^{1/2}$

Collider bounds : LHC



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

CMS 20/fb bound on the production rate requires

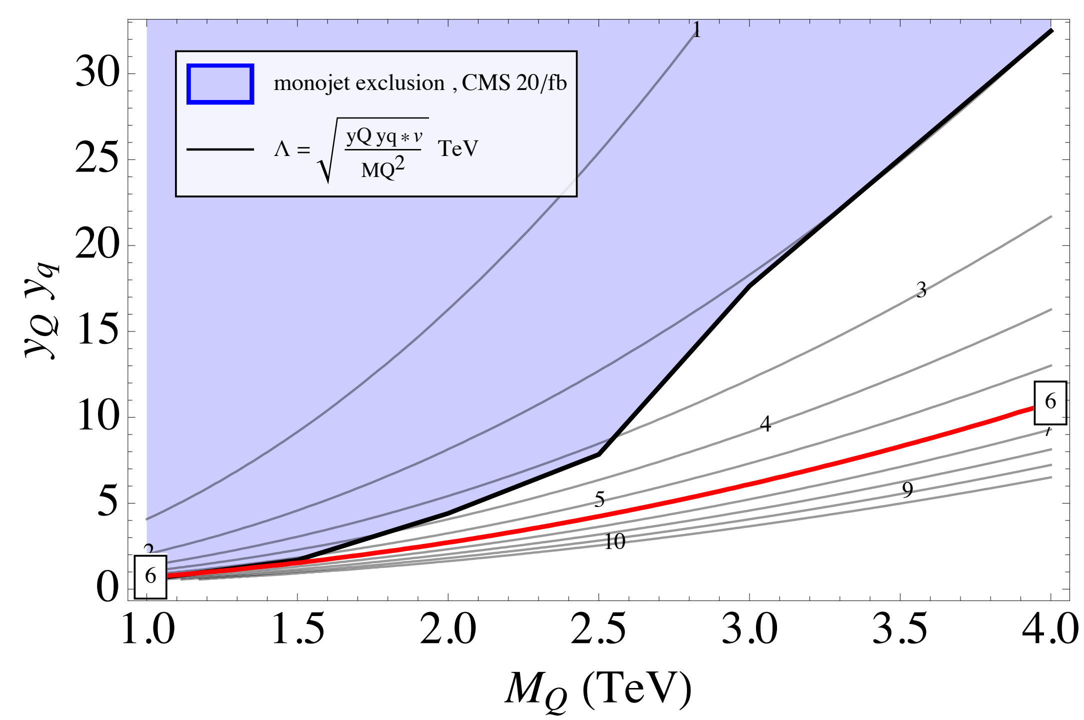
$$M_Q > 1.5\,\mathrm{TeV}$$

mono-jet $pp \to q^* \to \phi\,\psi_{Q,q} \to \phi\, j, \qquad pp \to \phi\,\phi + \mathrm{ISR}$

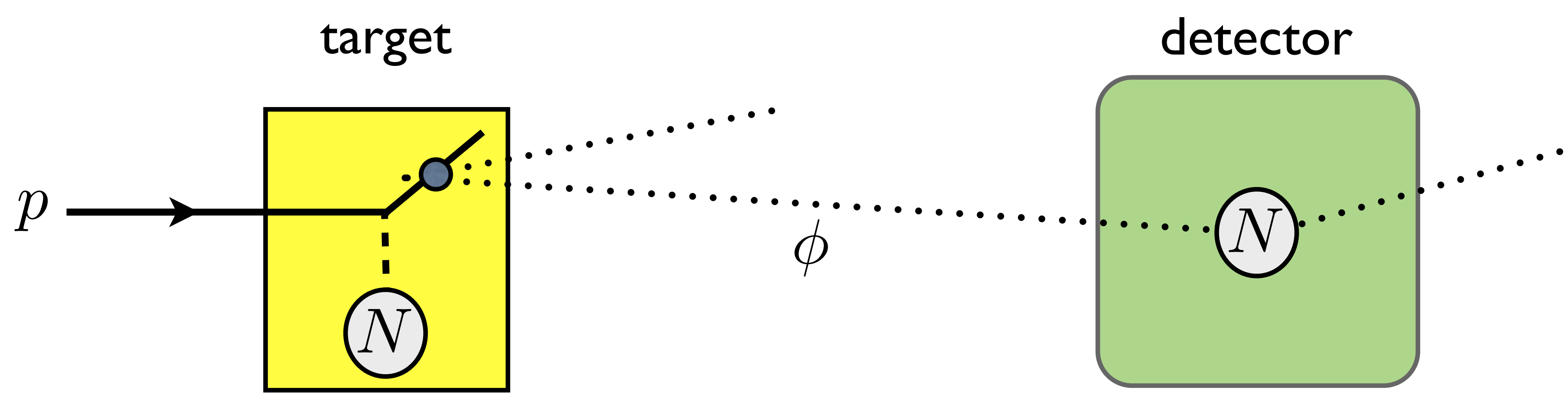
MG5+Pythia+PGS

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

No significant bound



Collider bounds : fixed target



	E_p	N_{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 m, 735 km	$\sim$ 10m
T2K [66–68]	30 GeV	$6.63 \cdot 10^{20}$	280m (INGRID in ND280)	$\sim$ 10 m
			295 km (Super-Kameiokande)	$\sim$ 40 m
MiniBooNE [69]	8.9 GeV	$6.5 \cdot 10^{20}(\nu)$, $11.3 \cdot 10^{20}(\bar{\nu})$	541 m	$\sim$ 10 m
LSND [70]	800 MeV	$1.8 \cdot 10^{23}$	30 m	0.3 m

ϕ production rate

geometrical suppression

even with detection efficiency =1
Ep = 120 GeV

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

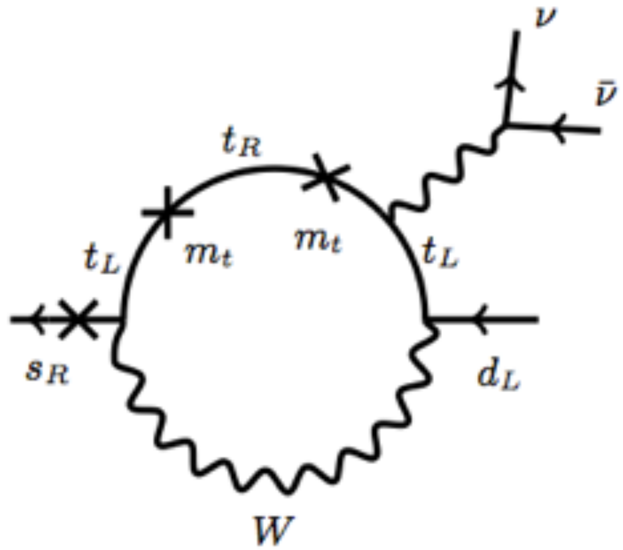
number of the observed events << 1

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

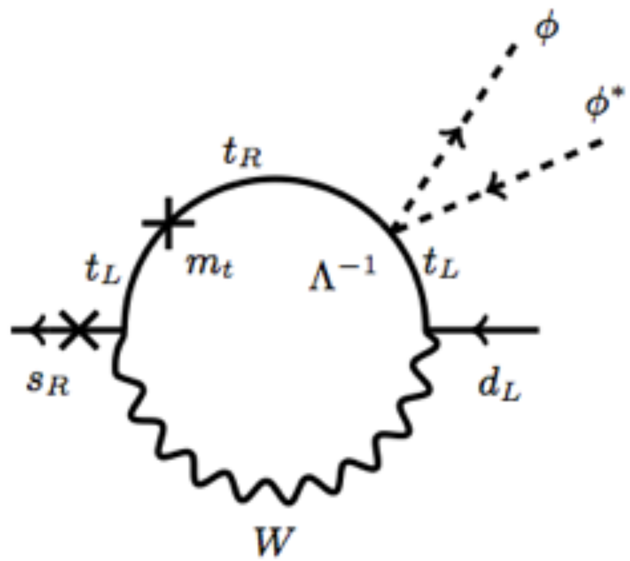
$$K^+ \to \pi^+ \, \phi \, \phi^*$$



current experimental precision

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

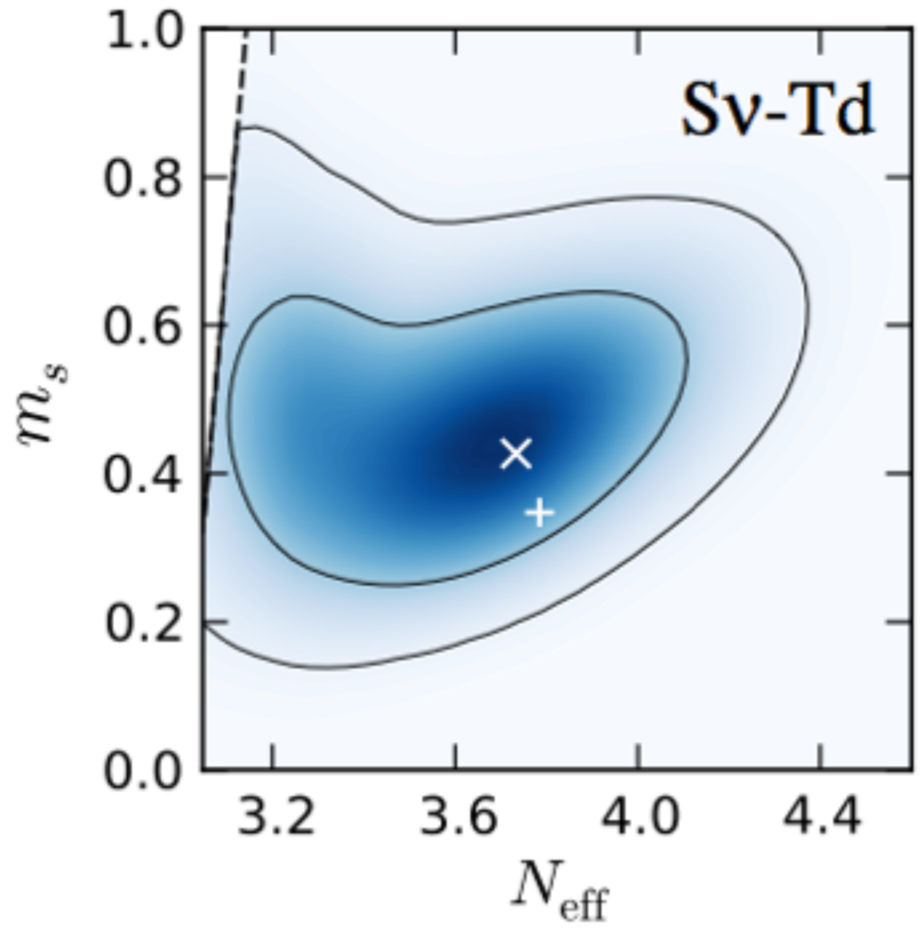
$$Br(K^+ \to \pi^+ \nu \bar{\nu})_{\rm SM} = (8.5 \pm 0.7) \cdot 10^{-11}$$



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

No significant bound

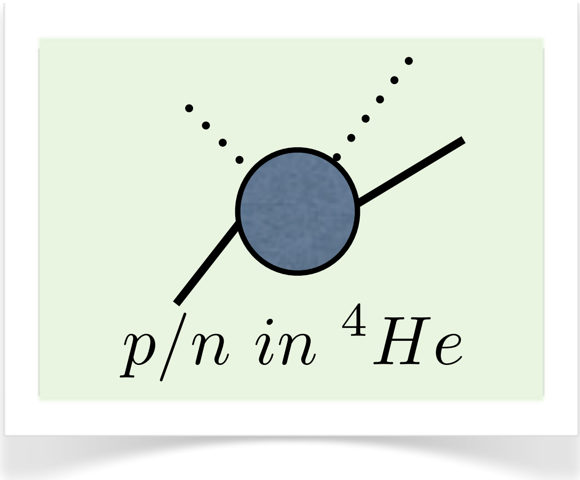
Bound on light sterile neutrino

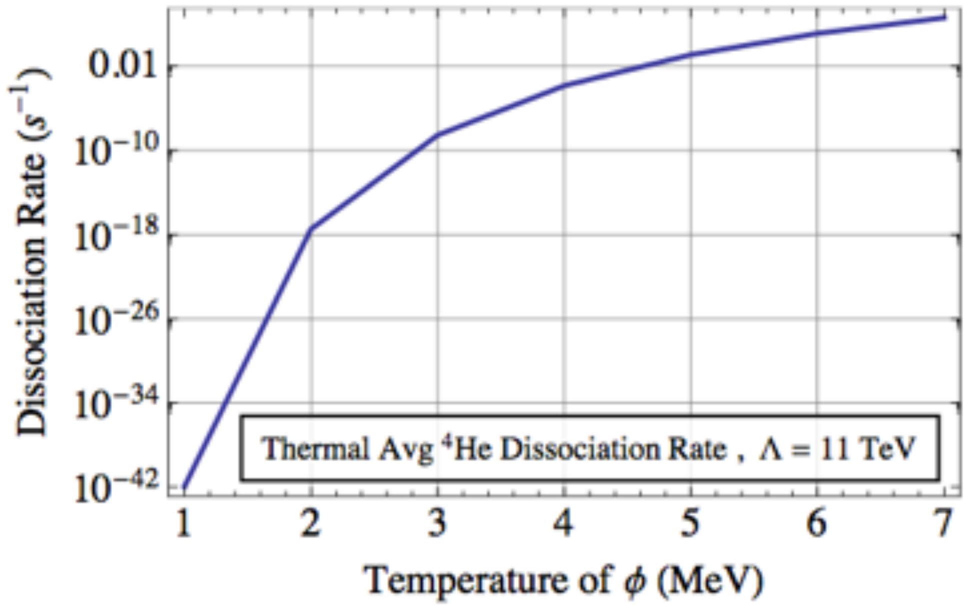


Planck+WMAP+H0+BAO+Xray cluster

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

Cosmological Constraints : 4He





- ϕ can in principle dissociated a 4He during the BBN time. However, the min recoil energy that a ϕ needs to kick out a nucleon from 4He is 7.1 MeV, which requires $E_\phi > 125\,\mathrm{MeV}$ when the temperature is below 10 MeV. $E_R^{max} = 2\,E_\phi^2/m_{^4He}$

- Calculating the dissociation rate by including the Boltzmann distribution sets a bound $\Lambda > 11\,\mathrm{TeV}$ when comparing the dissociation probability of 4He to the current precision $\frac{\delta n_{\mathrm{He}}}{n_{\mathrm{He}}} \simeq \frac{0.04}{0.26} = 15\,\%$

$m\phi = 0.2$ KeV

DOTTED = (collaboration bounds) → (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

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