ROADMAP OF DARK MATTER MODELS FOR RUN3

CERN WORKSHOP, 13-17 MAY 2024

Cosmological perspectives and constraints on t-channel models

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UCLouvain

CP3, UCLOUVAIN

Cosmology of t-channel models

- The work presented here is based on several contributions
  - T-channel white paper (cosmo section effort), together with M. Becker, E. Copello, M. Garny, J. Harz, J. Heisig, A. Ibarra, S. Khalil, M. Kirtiman, Y. Koay, L. Lopez Honorez, T. Murphy, L. Panizzi, D. Sengupta and S. Tentori
  - CA, B. Fuks, J. Heisig, M. Kraemer, L. Mantani, L. Panizzi, Phys. Rev. D 108 (2023) [arXiv:2307.10367 [hep-ph]]
  - CA, B. Fuks, L. Mantani, H. Meis, L. Panizzi, J. Salko, Phys. Lett. B 813 (2021) [arXiv:2010.136038 [hep-ph]]
  - CA, B. Fuks, L. Mantani, Eur. Phys J. C 80 (2020) [arXiv:2001.05024 [hep-ph]]

Cosmology of t-channel models

- Brief overview of the minimal simplified t-channel models
- Early universe physics and constraints on such models
- Today's probes from astroparticle and dark matter experiments
- Complementarity with collider searches for few selected benchmarks

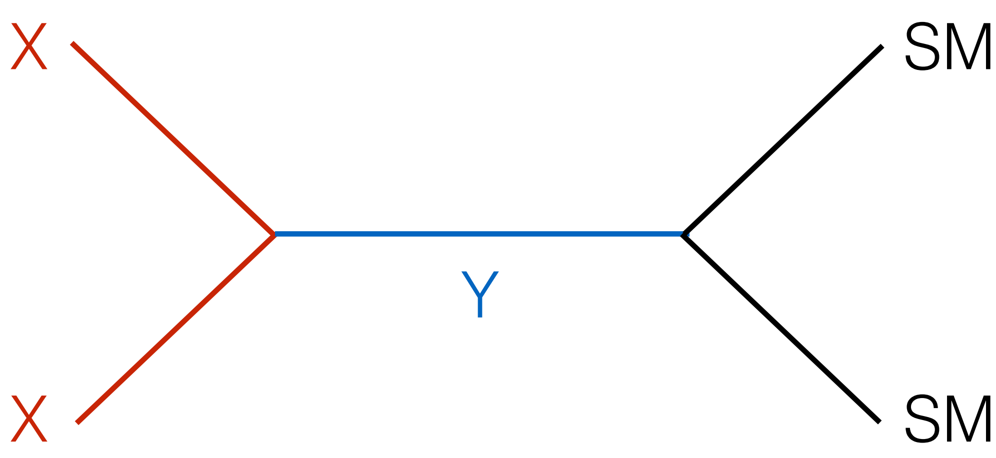
HERE CONSIDERED ONLY COLORED MEDIATORS COUPLING TO QUARKS

UNDERLINE THE DIFFERENCES WHEN RELEVANT THAT DEPEND ON THE QUARK GENERATION

HOWEVER T-CHANNEL CAN APPEAR UNDER MANY FORMS (SEE TALKS THIS MORNING) AND CAN BE LEPTOPHILIC AS WELL

Minimal t-channel model

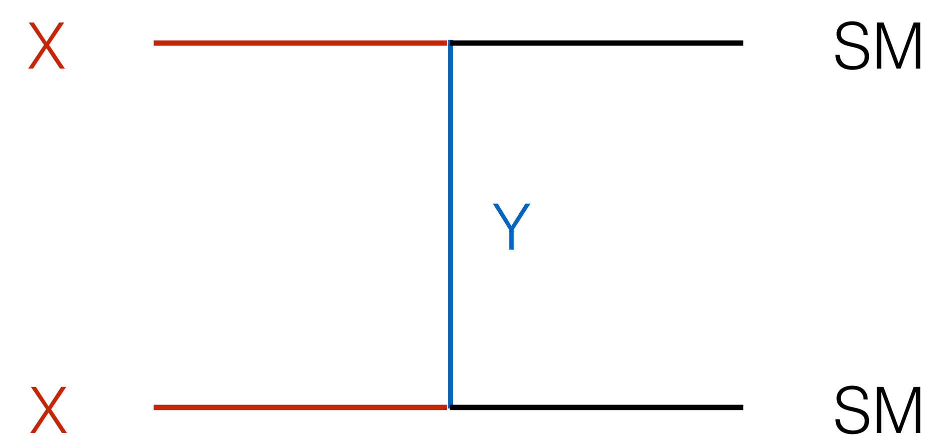
S-CHANNEL MODELS



- Y is even under the dark symmetry
- Y decays into 2 DM or 2 SM particles (typically quarks)
- Y is not coloured
- X is a SM gauge singlet

Several model files at LO/NLO available here

T-CHANNEL MODELS (this talk)



- Y is charged under the dark symmetry
- Y decays into 1 DM and 1 SM particle
- Y can be coloured if it couples to quarks as well as gluons
- X is a SM gauge singlet
- The model can be leptophilic

Minimal t-channel model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \mathcal{L}_F(\chi) + \mathcal{L}_F(\tilde\chi) + \mathcal{L}_S(S) + \mathcal{L}_S(\tilde S) + \mathcal{L}_V(V) + \mathcal{L}_V(\tilde V)$$

VERY GENERIC MODEL WITH 6 DARK MATTER CANDIDATES AND 24 MEDIATORS OF DIFFERENT SPIN

X

Field	Spin	Repr.	Self-conj.
$\tilde S$	0	$(\mathbf{1},\mathbf{1},0)$	yes
S	0	$(\mathbf{1},\mathbf{1},0)$	no
$\tilde\chi$	1/2	$(\mathbf{1},\mathbf{1},0)$	yes
χ	1/2	$(\mathbf{1},\mathbf{1},0)$	no
$\tilde V_\mu$	1	$(\mathbf{1},\mathbf{1},0)$	yes
V_μ	1	$(\mathbf{1},\mathbf{1},0)$	no
$\varphi_Q = \begin{pmatrix}\varphi_Q^{(u)}\\ \varphi_Q^{(d)}\end{pmatrix}$	0	$(\mathbf{3},\mathbf{2},\frac{1}{6})$	no
φ_u	0	$(\mathbf{3},\mathbf{1},\frac{2}{3})$	no
φ_d	0	$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	no

Y

$$\mathcal{L}_F(X) = \Big[\lambda_{\mathbf{Q}}\bar X Q \varphi_Q^\dagger + \lambda_{\mathbf{u}}\bar X u \varphi_u^\dagger + \lambda_{\mathbf{d}}\bar X d \varphi_d^\dagger + \text{h.c.}\Big]$$

$$\mathcal{L}_S(X) = \Big[\hat\lambda_{\mathbf{Q}}\bar\psi_Q Q X + \hat\lambda_{\mathbf{u}}\bar\psi_u u X + \hat\lambda_{\mathbf{d}}\bar\psi_d d X + \text{h.c.}\Big]$$

$$\mathcal{L}_V(X) = \Big[\hat\lambda_{\mathbf{Q}}\bar\psi_Q \not{X} Q + \hat\lambda_{\mathbf{u}}\bar\psi_u \not{X} u + \hat\lambda_{\mathbf{d}}\bar\psi_d \not{X} d + \text{h.c.}\Big]$$

UNIQUE IMPLEMENTATION FOR COLLIDER AND DM STUDIES

MODEL FILES AND DOCUMENTATION ARE AVAILABLE HERE:
HTTP://FEYNRULES.IRMP.UCL.AC.BE/WIKI/DMSIMPT

Minimal t-channel model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \mathcal{L}_F(\chi) + \mathcal{L}_F(\tilde{\chi}) + \mathcal{L}_S(S) + \mathcal{L}_S(\tilde{S}) + \mathcal{L}_V(V) + \mathcal{L}_V(\tilde{V})$$

VERY GENERIC MODEL WITH 6 DARK MATTER CANDIDATES AND 24 MEDIATORS OF DIFFERENT SPIN

X

Y

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ψ_u	1/2	$(\mathbf{3},\mathbf{1},\frac{2}{3})$	no
ψ_d	1/2	$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	no

$$\mathcal{L}_F(X) = \Big[\lambda_{\mathbf{Q}}\bar{X}Q\varphi_Q^\dagger + \lambda_{\mathbf{u}}\bar{X}u\varphi_u^\dagger + \lambda_{\mathbf{d}}\bar{X}d\varphi_d^\dagger + \text{h.c.}\Big]$$

$$\mathcal{L}_S(X) = \Big[\hat{\lambda}_{\mathbf{Q}}\bar{\psi}_Q QX + \hat{\lambda}_{\mathbf{u}}\bar{\psi}_u uX + \hat{\lambda}_{\mathbf{d}}\bar{\psi}_d dX + \text{h.c.}\Big]$$

$$\mathcal{L}_V(X) = \Big[\hat{\lambda}_{\mathbf{Q}}\bar{\psi}_Q \not{X} Q + \hat{\lambda}_{\mathbf{u}}\bar{\psi}_u \not{X} u + \hat{\lambda}_{\mathbf{d}}\bar{\psi}_d \not{X} d + \text{h.c.}\Big]$$

UNIQUE IMPLEMENTATION FOR COLLIDER AND DM STUDIES

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Minimal t-channel model

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VERY GENERIC MODEL WITH 6 DARK MATTER CANDIDATES AND 24 MEDIATORS OF DIFFERENT SPIN

X

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$$\mathcal{L}_F(X) = \left[\lambda_{\mathbf{Q}}\bar X Q\varphi_Q^\dagger + \lambda_{\mathbf{u}}\bar X u\varphi_u^\dagger + \lambda_{\mathbf{d}}\bar X d\varphi_d^\dagger + \text{h.c.}\right]$$

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New couplings
3x3 matrices in flavour space
real and flavour diagonal

UNIQUE IMPLEMENTATION FOR COLLIDER AND DM STUDIES

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Minimal t-channel model

Name	DM	Mediators	Parameters
S3M_uni	$\tilde{\chi}$	$\varphi_{Q_f},\, \varphi_{u_f},\, \varphi_{d_f}$	$M_\varphi,\, M_\chi,\, \lambda_\varphi$
S3D_uni	χ		
S3M_3rd	$\tilde{\chi}$	$\varphi_{Q_3},\, \varphi_{u_3},\, \varphi_{d_3}$	
S3D_3rd	χ		
S3M_uR	$\tilde{\chi}$	φ_{u_1}	
S3D_uR	χ		
F3S_uni	$\tilde{S}$	$\psi_{Q_f},\, \psi_{u_f},\, \psi_{d_f}$	$M_S,\, M_\psi,\, \hat{\lambda}_\psi$
F3C_uni	S		
F3S_3rd	$\tilde{S}$	$\psi_{Q_3},\, \psi_{u_3},\, \psi_{d_3}$	
F3C_3rd	S		
F3S_uR	$\tilde{S}$	ψ_{u_1}	
F3C_uR	S		
F3V_uni	$\tilde{V}_\mu$	$\psi_{Q_f},\, \psi_{u_f},\, \psi_{d_f}$	$M_V,\, M_\psi,\, \hat{\lambda}_\psi$
F3W_uni	V_μ		
F3V_3rd	$\tilde{V}_\mu$	$\psi_{Q_3},\, \psi_{u_3},\, \psi_{d_3}$	
F3W_3rd	V_μ		
F3V_uR	$\tilde{V}_\mu$	ψ_{u_1}	
F3W_uR	V_μ		

THE GENERIC MODEL HAS SEVERAL RESTRICTIONS WHERE THE UNDESIRED FIELDS ARE DECOUPLED AND INTERACTIONS ARE SET TO ZERO

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S3D_3rd	χ		
S3M_uR	$\tilde{\chi}$	φ_{u_1}	
S3D_uR	χ		
F3S_uni	$\tilde{S}$	$\psi_{Q_f}, \psi_{u_f}, \psi_{d_f}$	$M_S, M_\psi, \hat{\lambda}_\psi$
F3C_uni	S		
F3S_3rd	$\tilde{S}$	$\psi_{Q_3}, \psi_{u_3}, \psi_{d_3}$	
F3C_3rd	S		
F3S_uR	$\tilde{S}$	ψ_{u_1}	
F3C_uR	S		
F3V_uni	$\tilde{V}_\mu$	$\psi_{Q_f}, \psi_{u_f}, \psi_{d_f}$	$M_V, M_\psi, \hat{\lambda}_\psi$
F3W_uni	V_μ		
F3V_3rd	$\tilde{V}_\mu$	$\psi_{Q_3}, \psi_{u_3}, \psi_{d_3}$	
F3W_3rd	V_μ		
F3V_uR	$\tilde{V}_\mu$	ψ_{u_1}	
F3W_uR	V_μ		

THE GENERIC MODEL HAS SEVERAL RESTRICTIONS WHERE THE UNDESIRED FIELDS ARE DECOUPLED AND INTERACTIONS ARE SET TO ZERO

Any restriction has
3 free model parameters:
DM and mediator masses + coupling
(M_X, M_Y, λ)

Minimal t-channel model

Name	DM	Mediators	Parameters
S3M_uni	$\tilde{\chi}$	$\varphi_{Q_f}, \varphi_{u_f}, \varphi_{d_f}$	
S3D_uni	χ		
S3M_3rd	$\tilde{\chi}$	$\varphi_{Q_3}, \varphi_{u_3}, \varphi_{d_3}$	$M_\varphi,\ M_\chi,\ \lambda_\varphi$
S3D_3rd	χ		
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S3D_uR	χ		
F3S_uni	$\tilde{S}$	$\psi_{Q_f}, \psi_{u_f}, \psi_{d_f}$	
F3C_uni	S		
F3S_3rd	$\tilde{S}$	$\psi_{Q_3}, \psi_{u_3}, \psi_{d_3}$	$M_S,\ M_\psi,\ \hat{\lambda}_\psi$
F3C_3rd	S		
F3S_uR	$\tilde{S}$	ψ_{u_1}	
F3C_uR	S		
F3V_uni	$\tilde{V}_\mu$	$\psi_{Q_f}, \psi_{u_f}, \psi_{d_f}$	
F3W_uni	V_μ		
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F3W_3rd	V_μ		
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Any restriction has
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coupling only to quark up-right

Minimal t-channel model

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S3M_uni	$\tilde{\chi}$	$\varphi_{Q_f}, \varphi_{u_f}, \varphi_{d_f}$	$M_\varphi,\ M_\chi,\ \lambda_\varphi$
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F3W_3rd	V_μ		
F3V_uR	$\tilde{V}_\mu$	ψ_{u_1}	
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THE GENERIC MODEL HAS SEVERAL RESTRICTIONS WHERE THE UNDESIRED FIELDS ARE DECOUPLED AND INTERACTIONS ARE SET TO ZERO

Any restriction has
3 free model parameters:
DM and mediator masses + coupling
(M_X, M_Y, λ)

F3V_3rd → coupling only to b and t quarks

F3V_uR → coupling only to quark up-right

Minimal t-channel model

Name	DM	Mediators	Parameters
S3M_uni	$\tilde{\chi}$	$\varphi_{Q_f}, \varphi_{u_f}, \varphi_{d_f}$	
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S3M_3rd	$\tilde{\chi}$	$\varphi_{Q_3}, \varphi_{u_3}, \varphi_{d_3}$	$M_\varphi, M_\chi, \lambda_\varphi$
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F3C_uni	S		
F3S_3rd	$\tilde{S}$	$\psi_{Q_3}, \psi_{u_3}, \psi_{d_3}$	$M_S, M_\psi, \hat{\lambda}_\psi$
F3C_3rd	S		
F3S_uR	$\tilde{S}$	ψ_{u_1}	
F3C_uR	S		
F3V_uni	$\tilde{V}_\mu$	$\psi_{Q_f}, \psi_{u_f}, \psi_{d_f}$	
F3W_uni	V_μ		
F3V_3rd	$\tilde{V}_\mu$	$\psi_{Q_3}, \psi_{u_3}, \psi_{d_3}$	$M_V, M_\psi, \hat{\lambda}_\psi$
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THE GENERIC MODEL HAS SEVERAL RESTRICTIONS WHERE THE UNDESIRED FIELDS ARE DECOUPLED AND INTERACTIONS ARE SET TO ZERO

Any restriction has
3 free model parameters:
DM and mediator masses + coupling
(M_X, M_Y, λ)

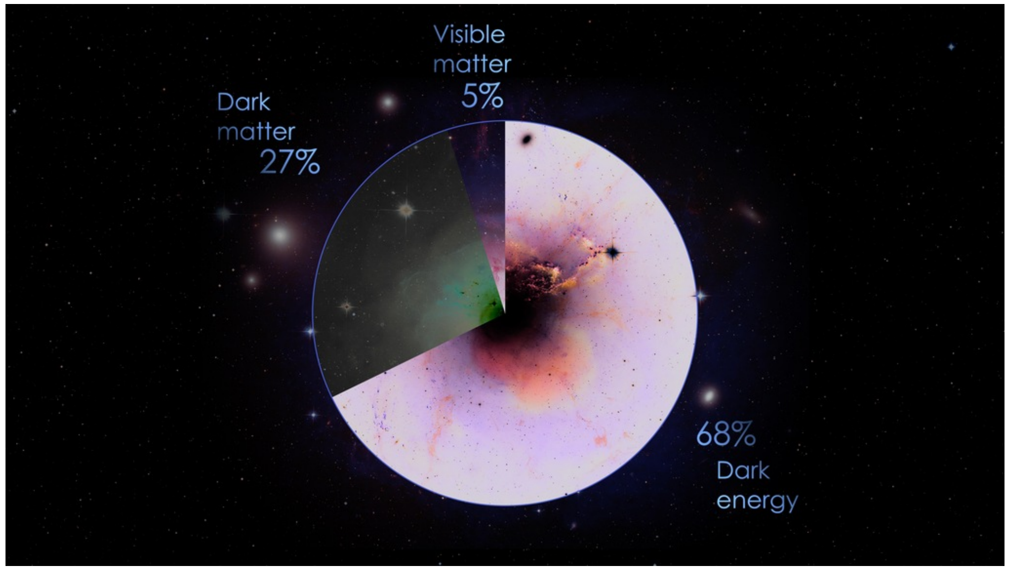
_uni → coupling to all quarks

_3rd → coupling only to b and t quarks

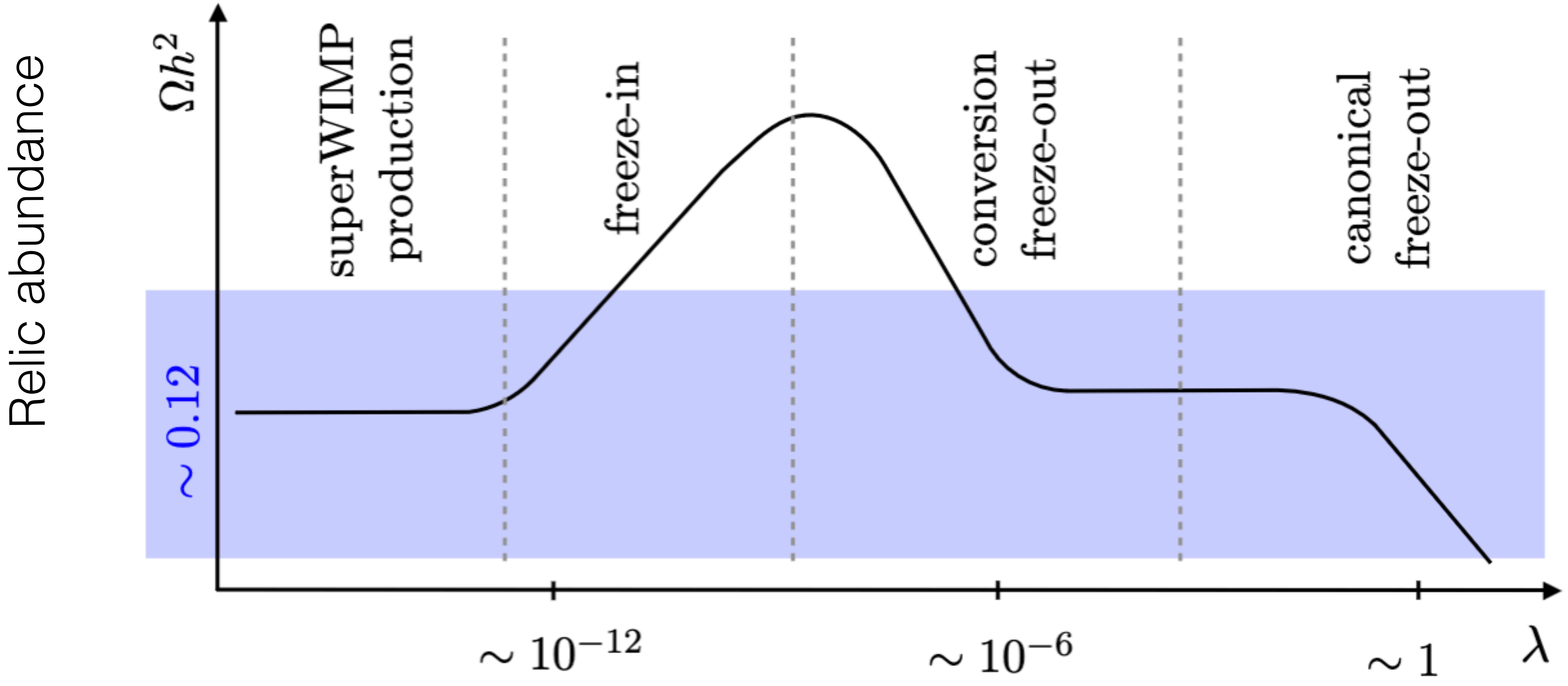
_uR → coupling only to quark up-right

Early universe

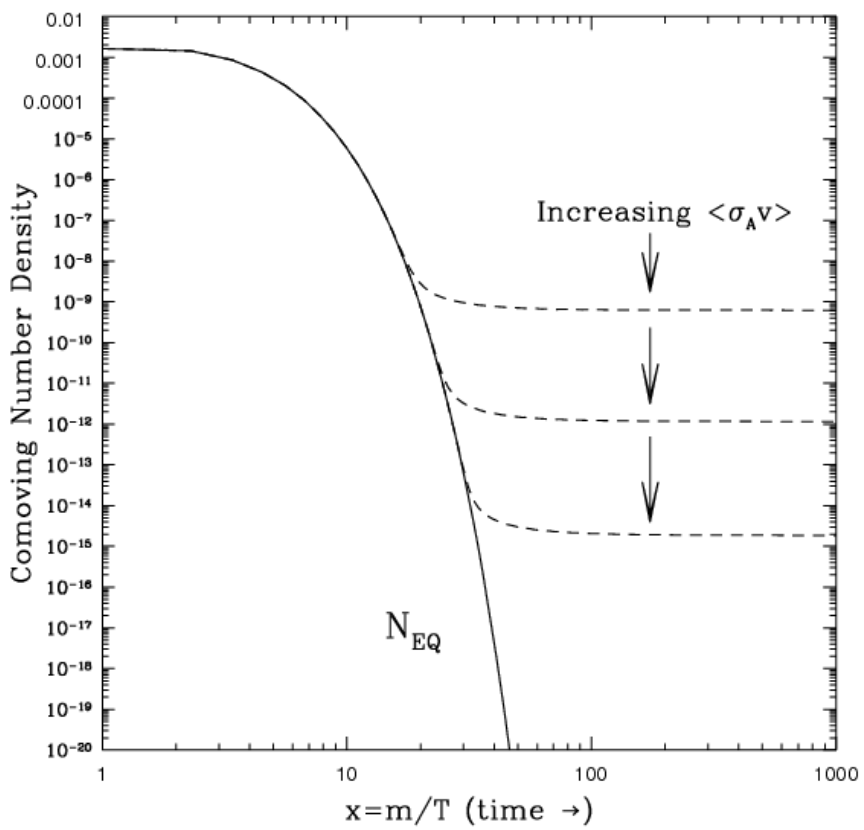
Credit:NASA



ΩH² =0.12 PLANCK SATELLITE [ARXIV:1807.06209]



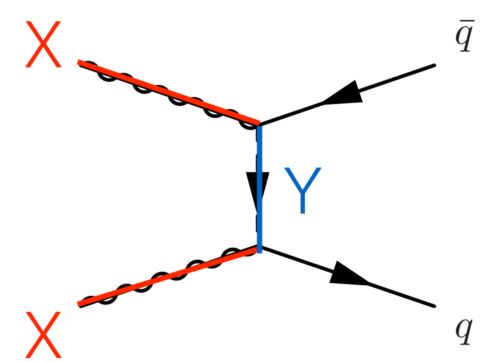
Early universe: freeze-out



LARGE COUPLING = WIMP

DETECTABLE SIGNATURES IN DIRECT, INDIRECT SEARCH EXPERIMENT FOR DARK MATTER AND AT COLLIDERS

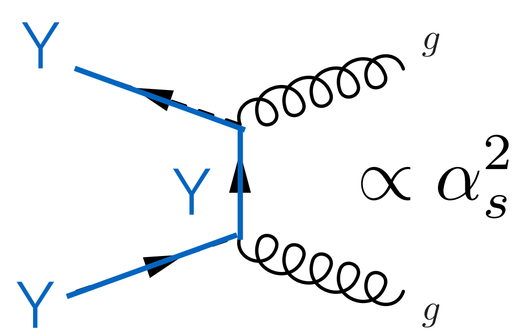
TYPICALLY LO PROCESSES ARE DOMINANT



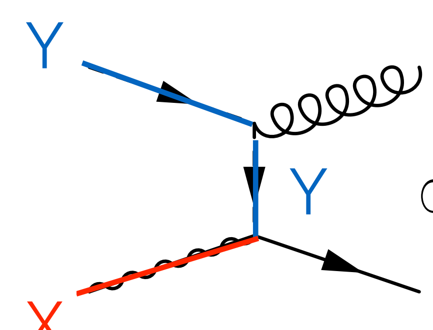
DM annihilation

$\propto \lambda^4$

coannihilation (compressed spectrum)



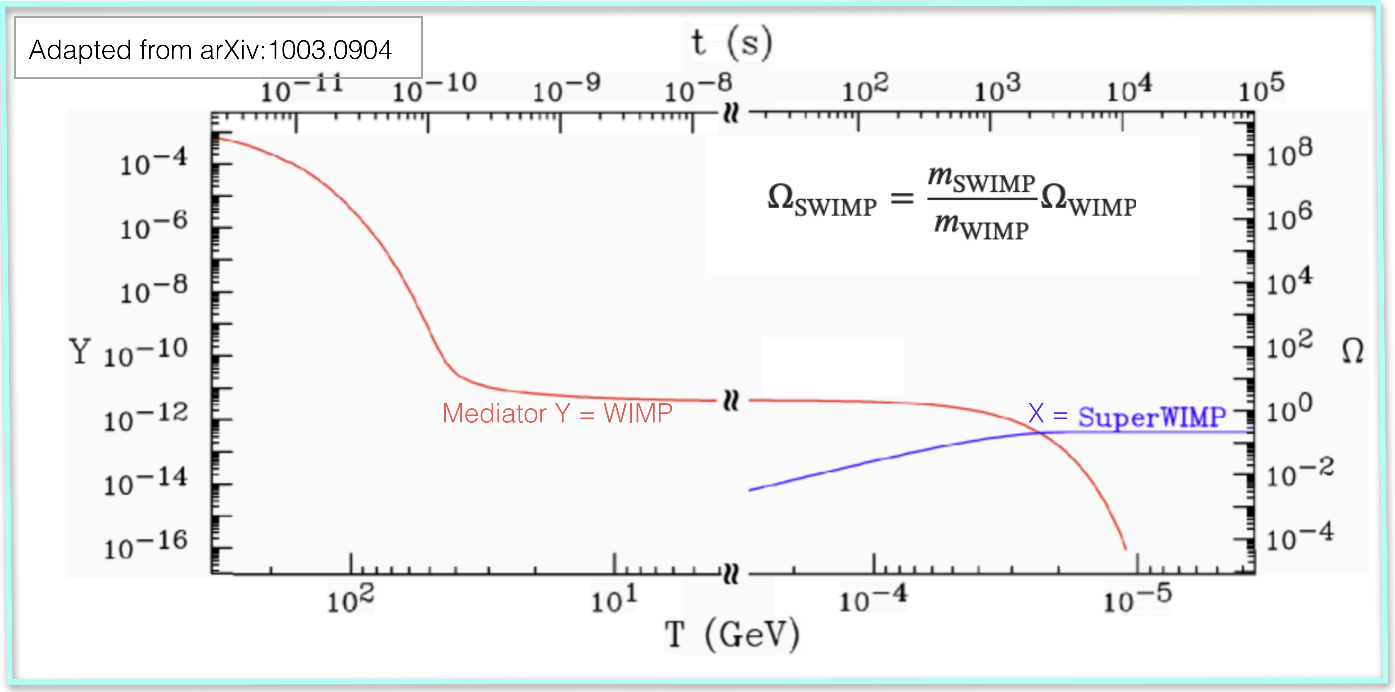
$\propto \alpha_s^2$

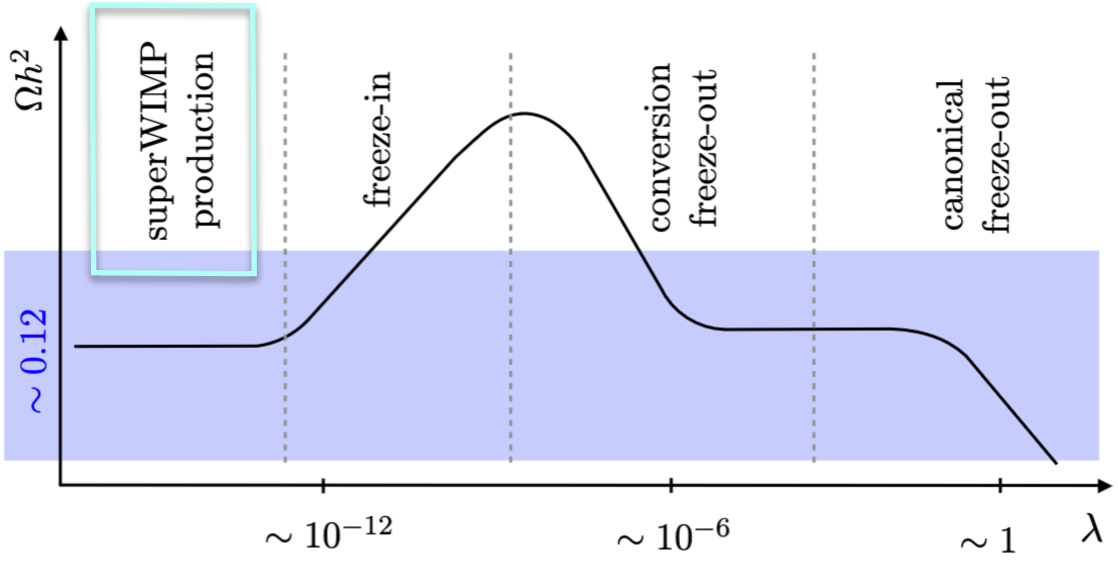


$\propto \lambda^2 \alpha_s$

- Sommerfeld enhancement and bounds state formation can be relevant when mediators are light (YY —> qq, YY —> gg)
- For d-wave suppressed annihilation cross-sections NLO corrections are relevant
- Pheno is the basically the same for all quark flavours (threshold effects for heavy quarks)

Early universe: small couplings (FIMPs)





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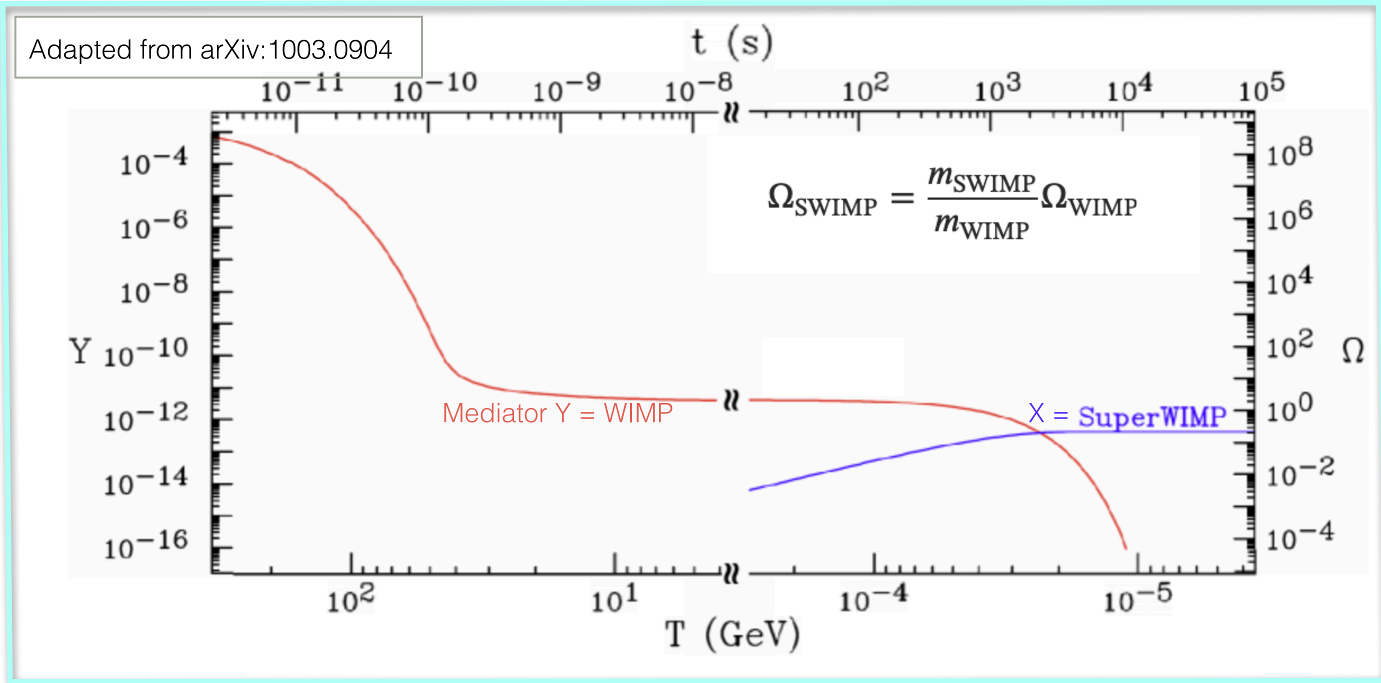

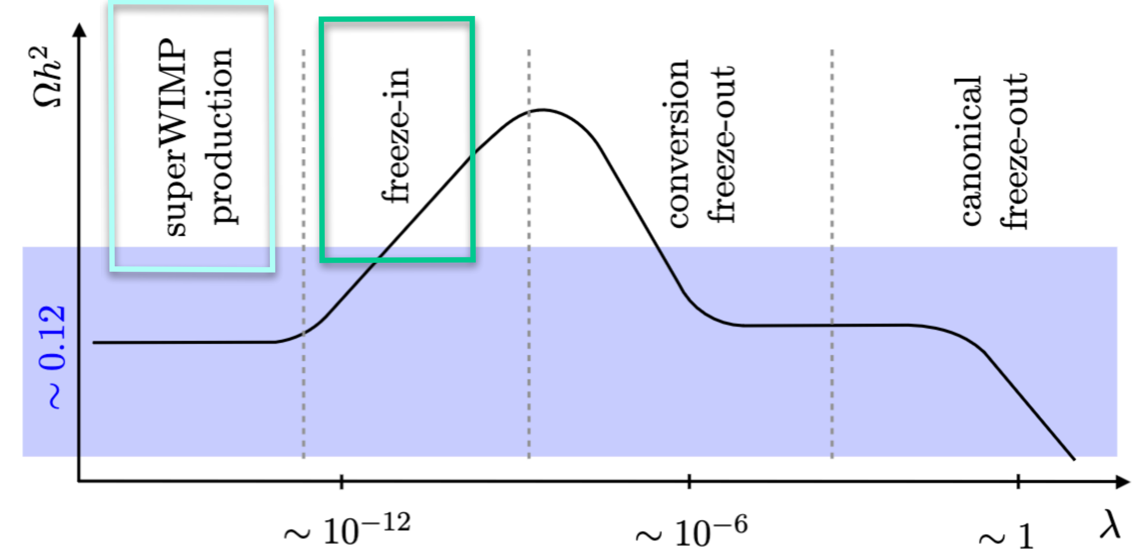

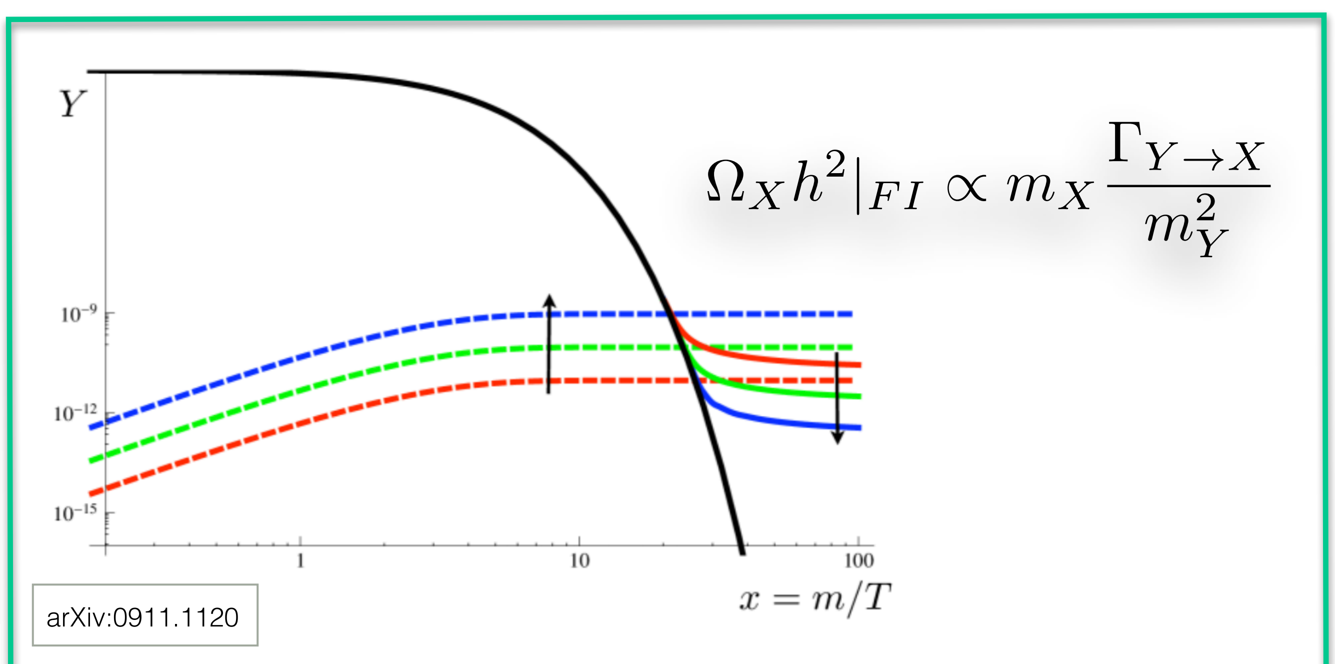

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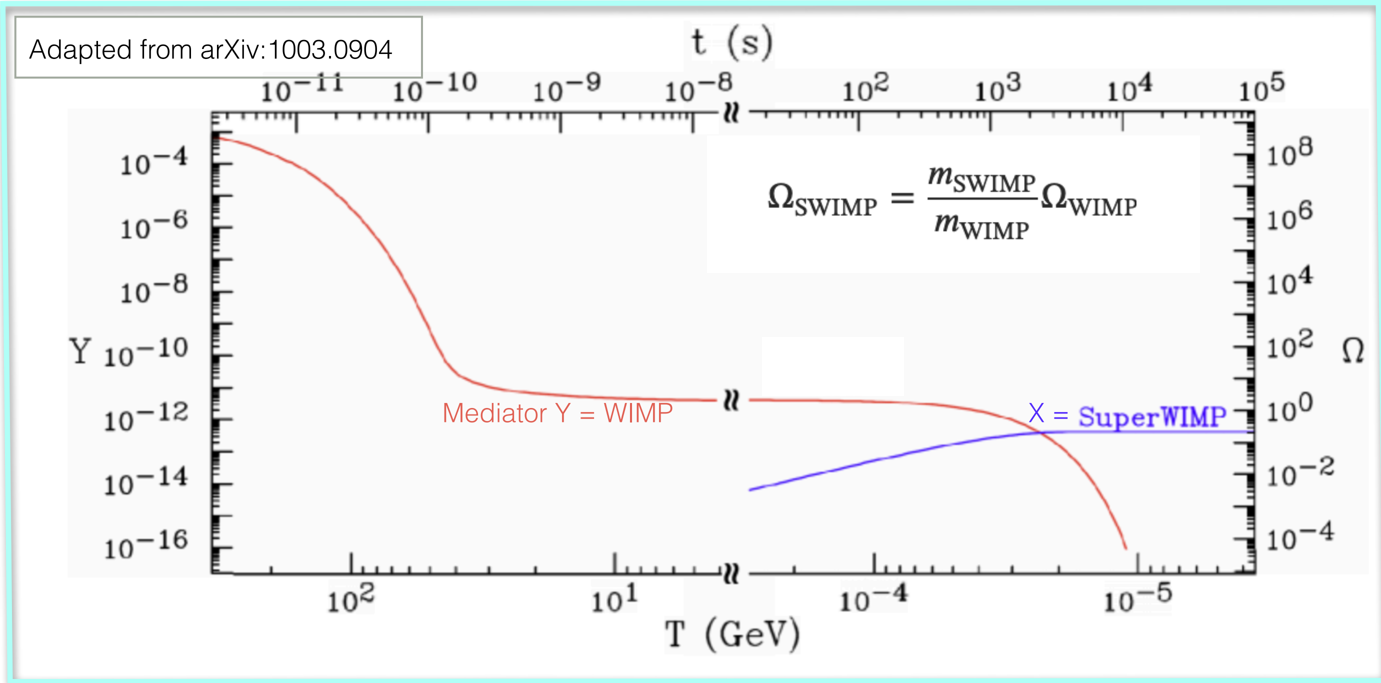
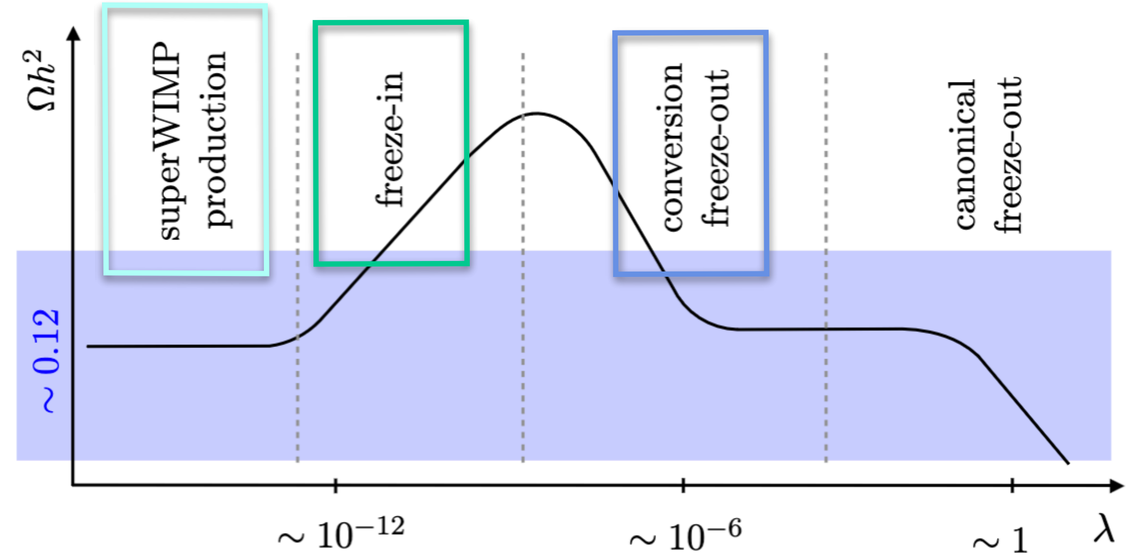
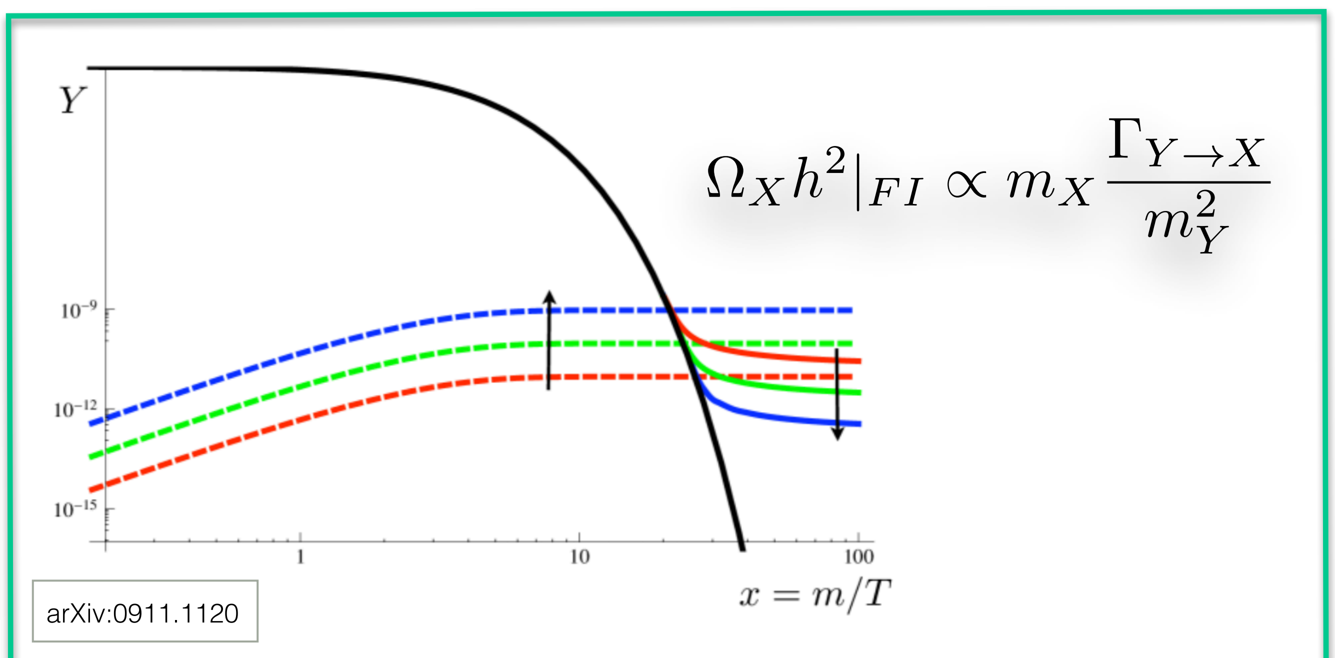


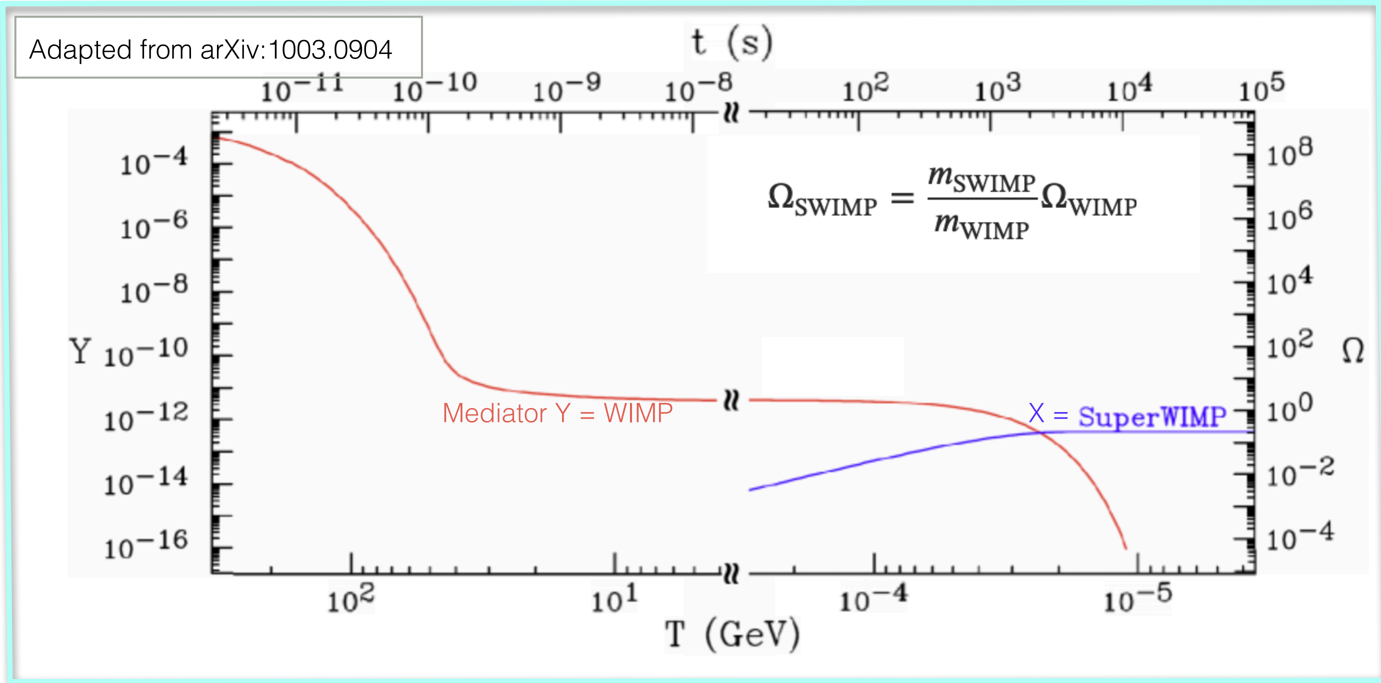


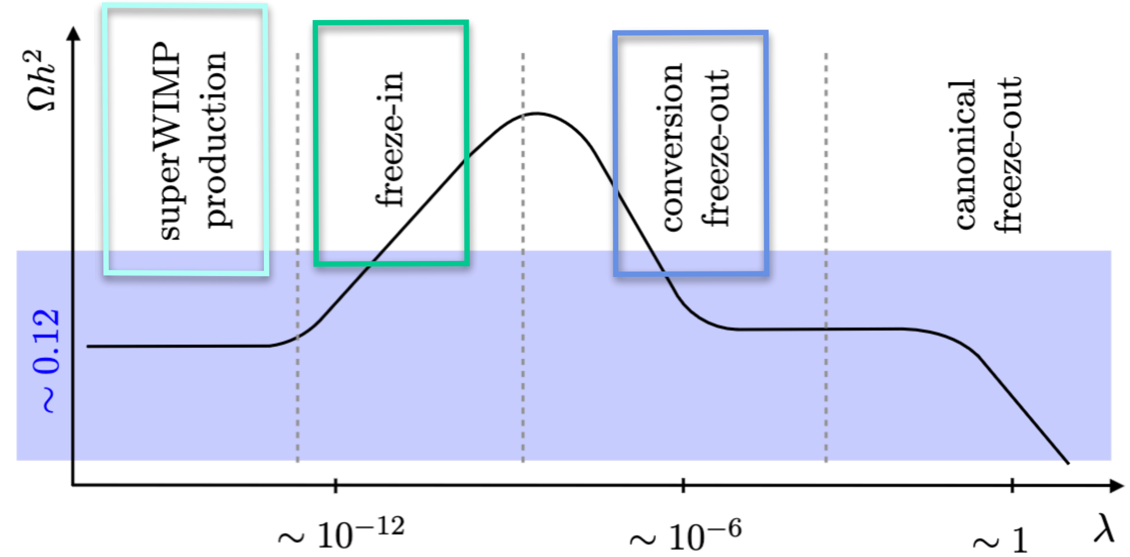
- Annihilation XX, YX, YY —> AB becomes inefficient
- Conversions such as Y -> XA, YA -> XB (A,B=SM) lead the freeze-out process

Much more in J. Heisig talk



Early universe: small couplings (FIMPs)





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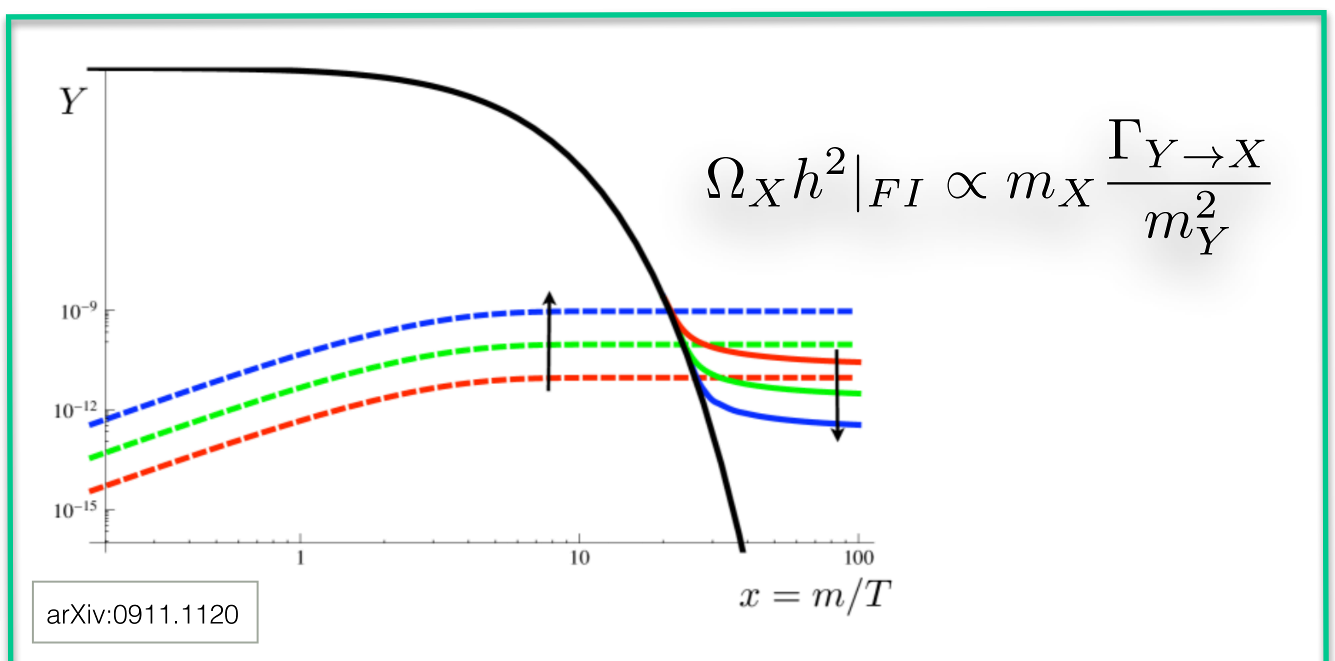
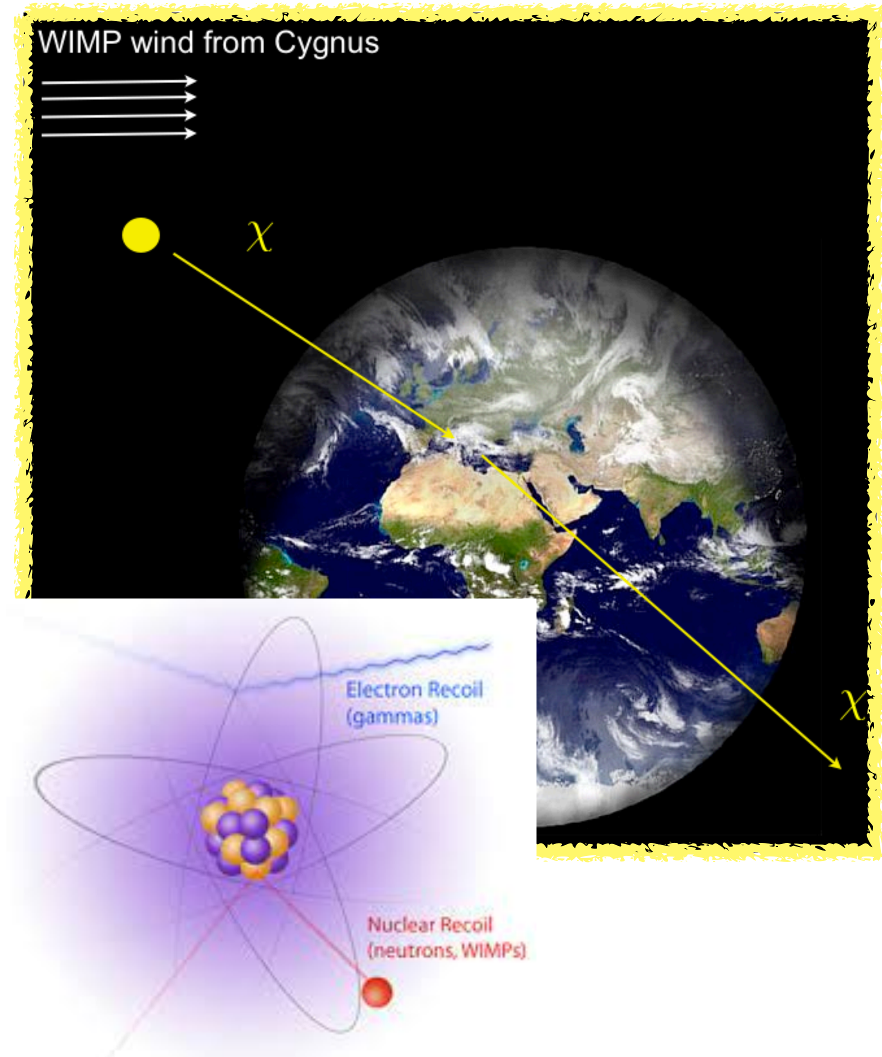


SMALL COUPLINGS

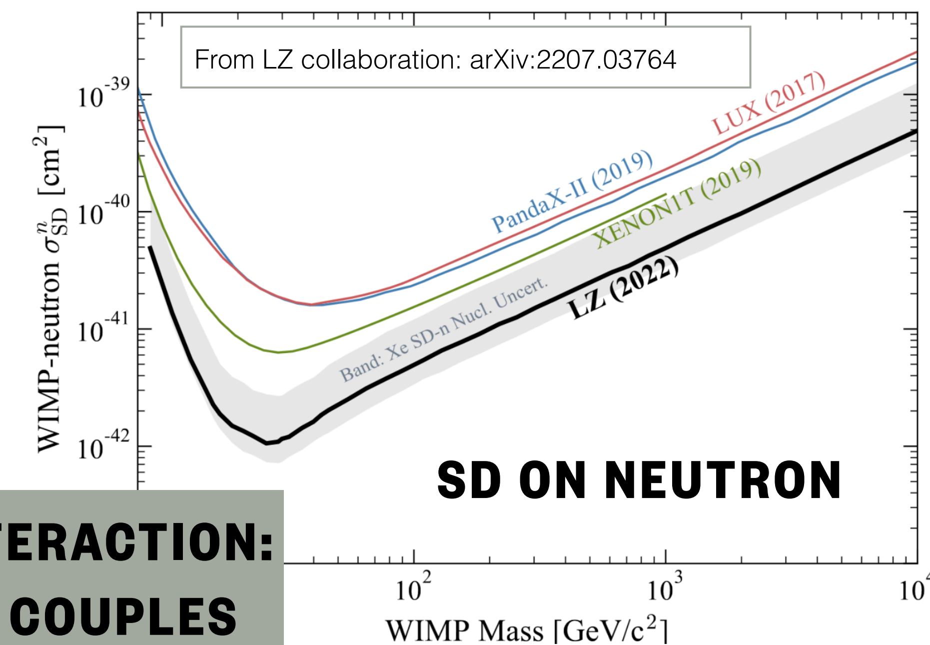
- CHALLENGING TO SEE IN DARK MATTER SEARCHES
- PROVIDE LLP SIGNALS AT LHC
- CAN HAVE VERY COMPRESSED SPECTRUM
- CONSTRAINTS FROM EARLY UNIVERSE (E.G. LYMAN-α, CMB, BBN)

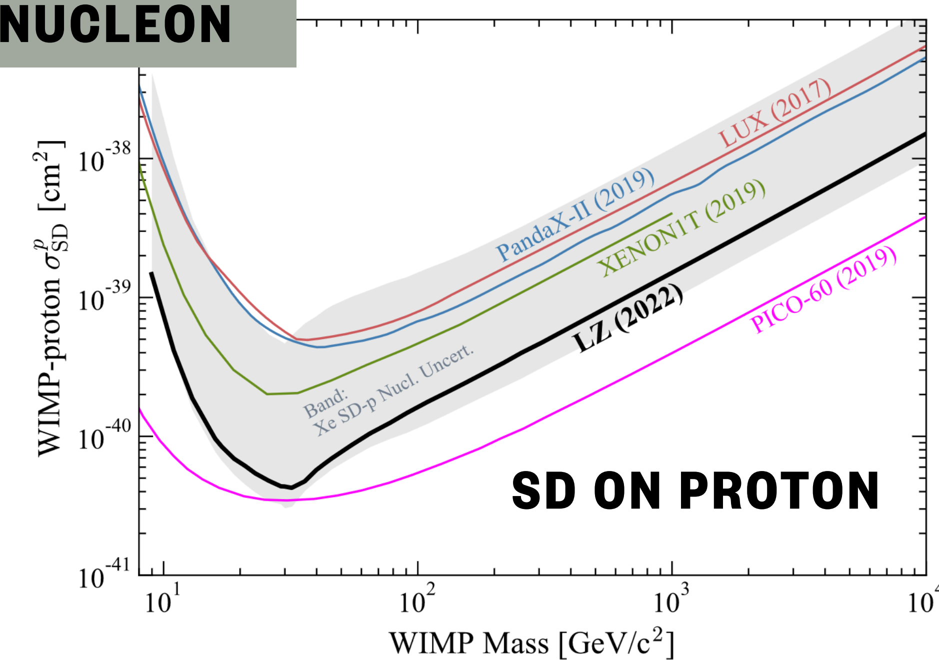
Direct detection of WIMPs



DARK MATTER - NUCLEON SCATTERING IN UNDERGROUND DETECTOR

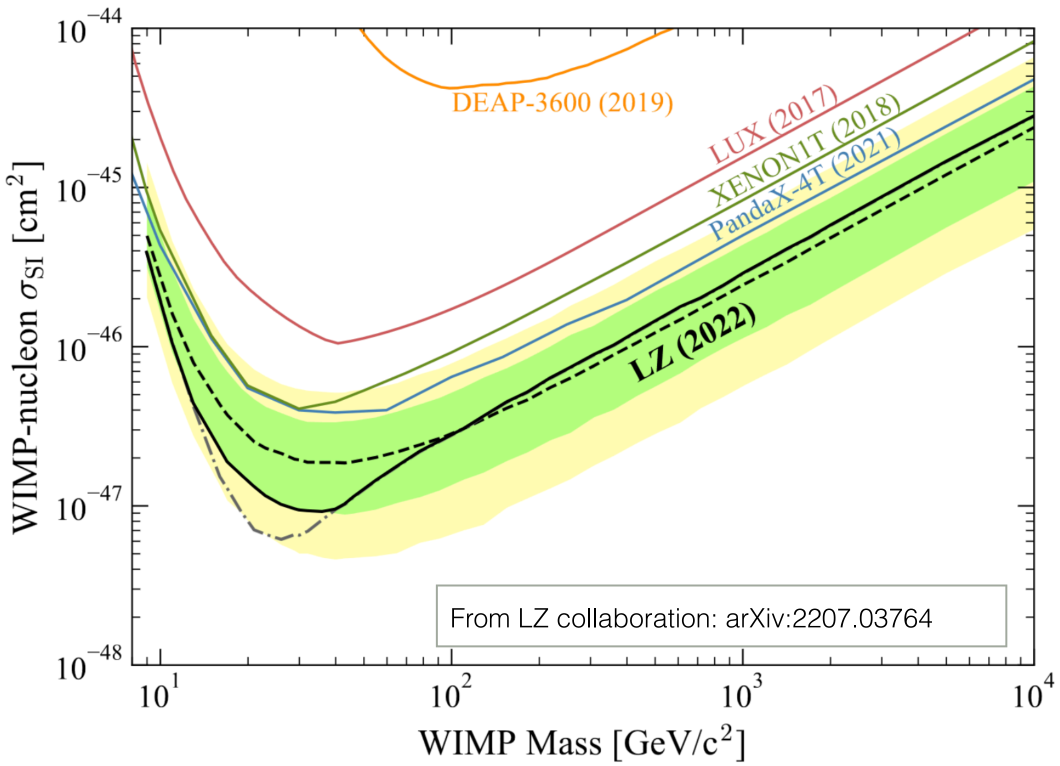
SPIN-DEPENDENT INTERACTION: DARK MATTER SPIN COUPLES TO THE UNPAIRED NUCLEON

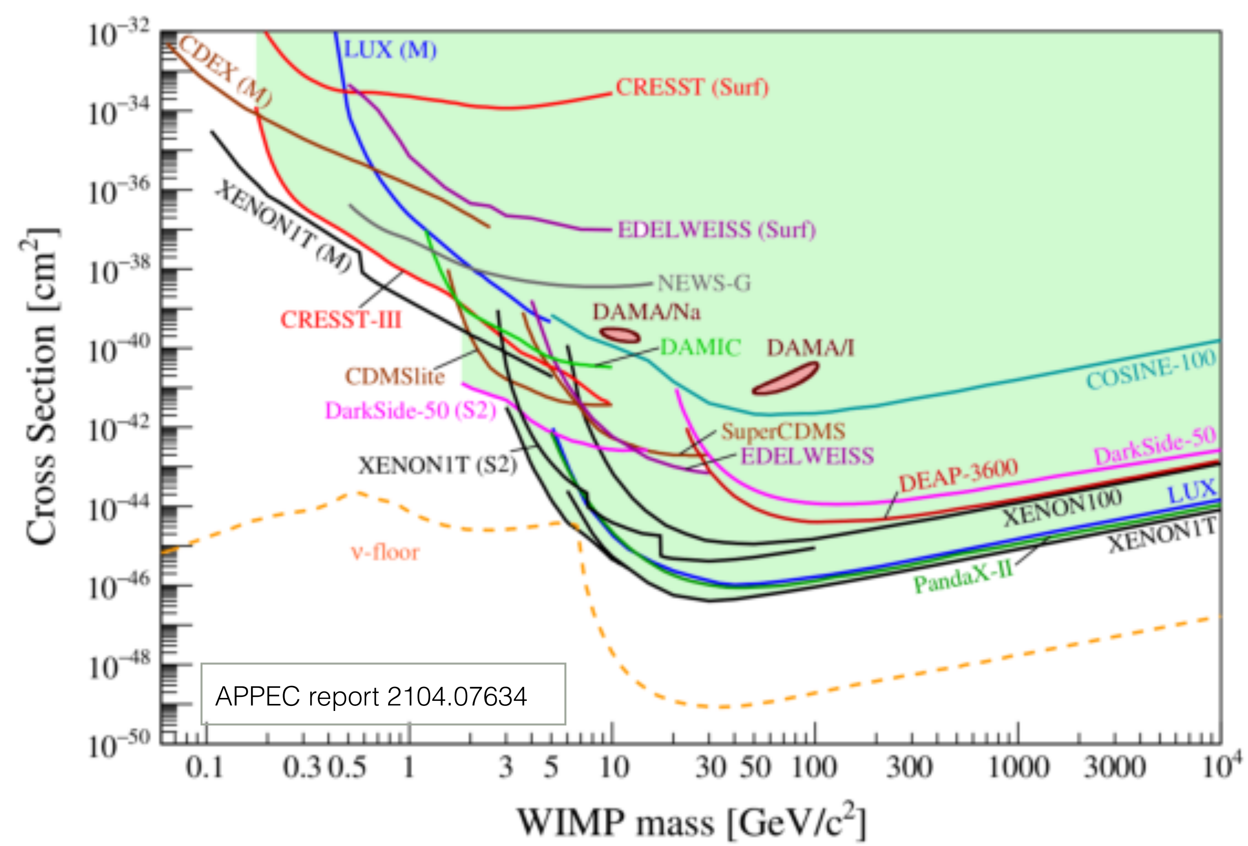




Direct detection of WIMPs

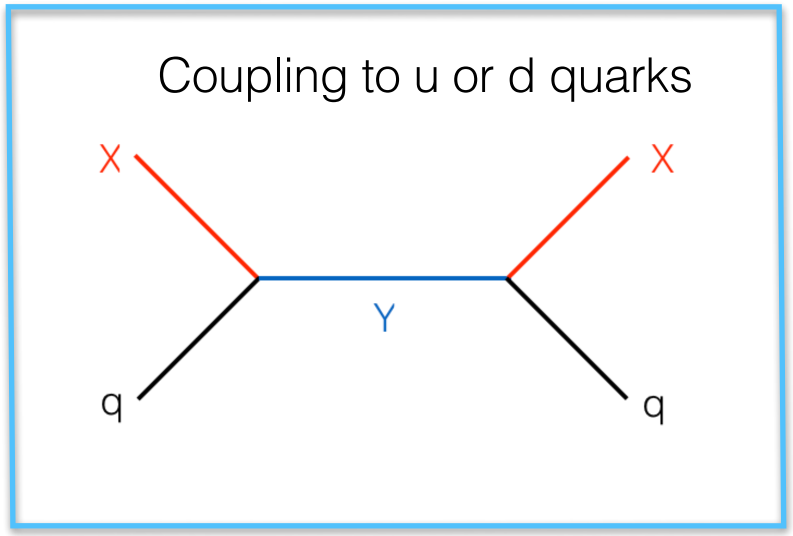
SPIN-INDEPENDENT INTERACTION: DARK MATTER COUPLES TO ALL NUCLEONS (SENSITIVE TO A²)

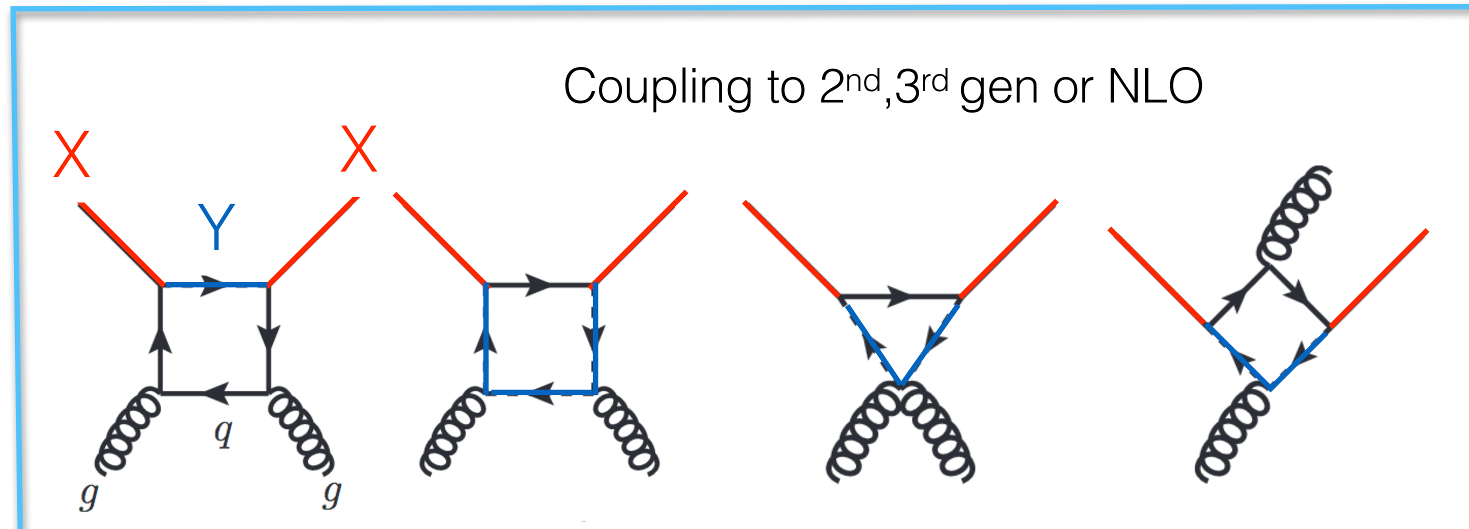




DIRECT DETECTION SENSITIVE UP TO TENS OF TEV IN DARK MATTER MASS ($\propto m_X^{-2}$)

Direct detection of WIMPs

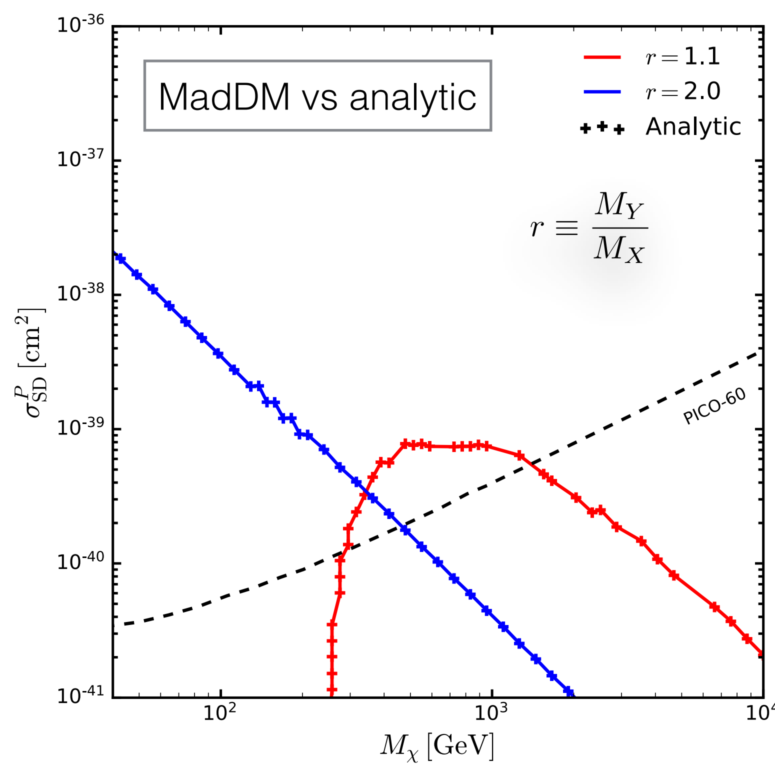


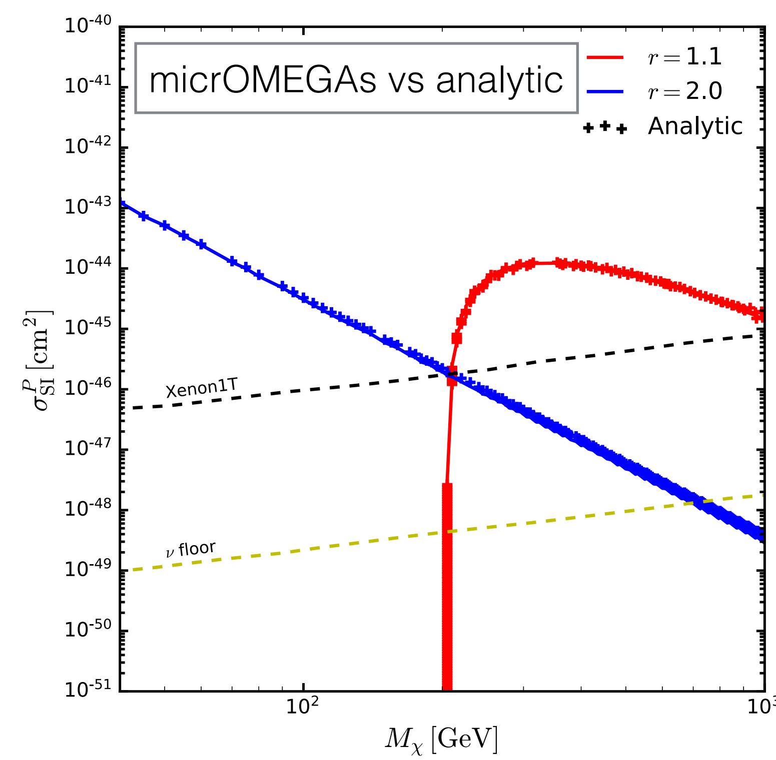


GIVEN THE EXPERIMENTAL SENSITIVITY, NLO MATTERS

FOR MAJORANA COUPLING TO UR (S3M_UR) DIRECT DETECTION IS:

- LO FOR SPIN-DEPENDENT (MADDM TOOL)
- NLO FOR SPIN-INDEPENDENT (MICROMEGAS TOOL)
- ANALYTIC EXPRESSIONS [HISANO ET AL. (JHEP 2015)]

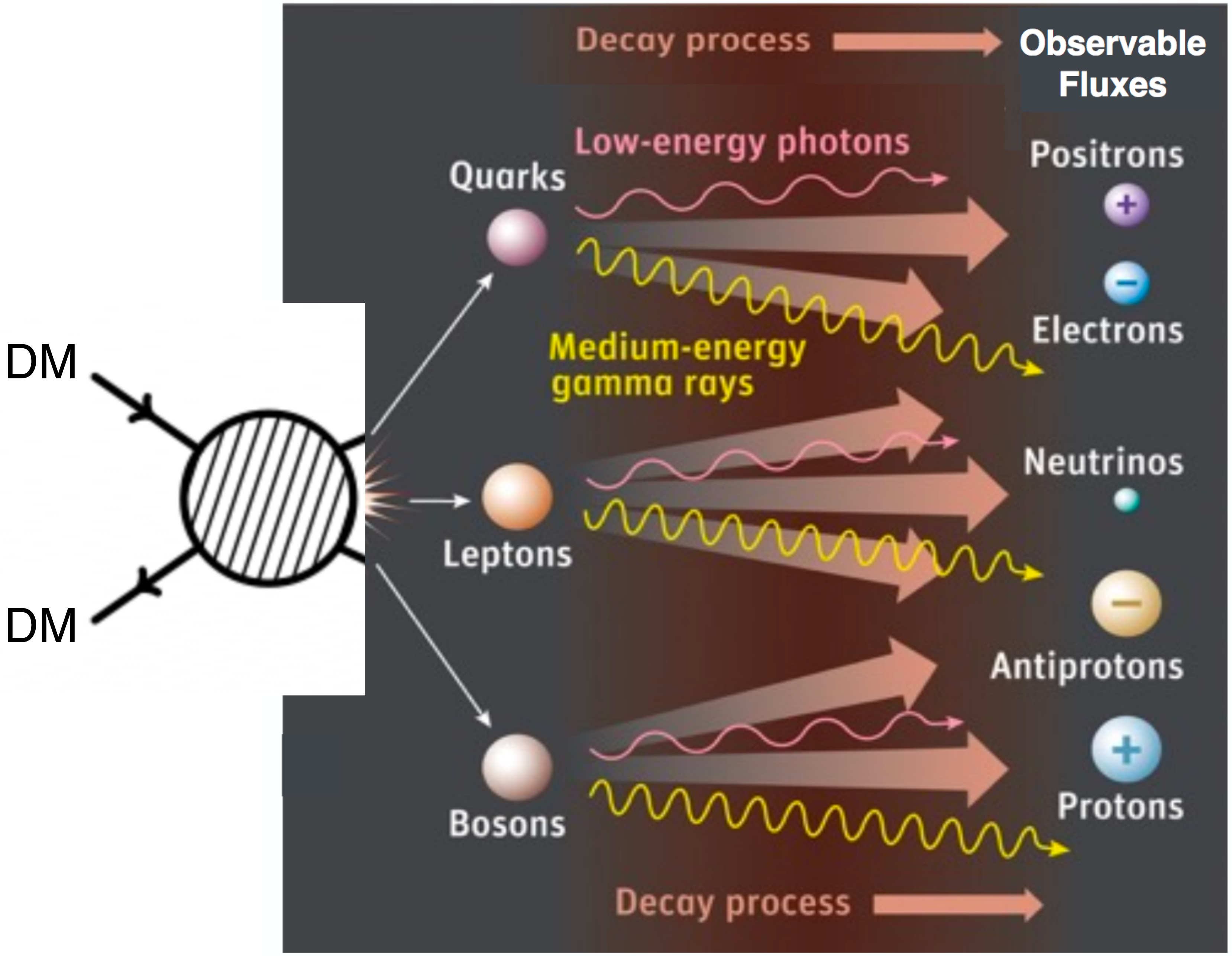




UFO AT LO AND NLO CAN BE USED DIRECTLY INTO DARK MATTER TOOLS

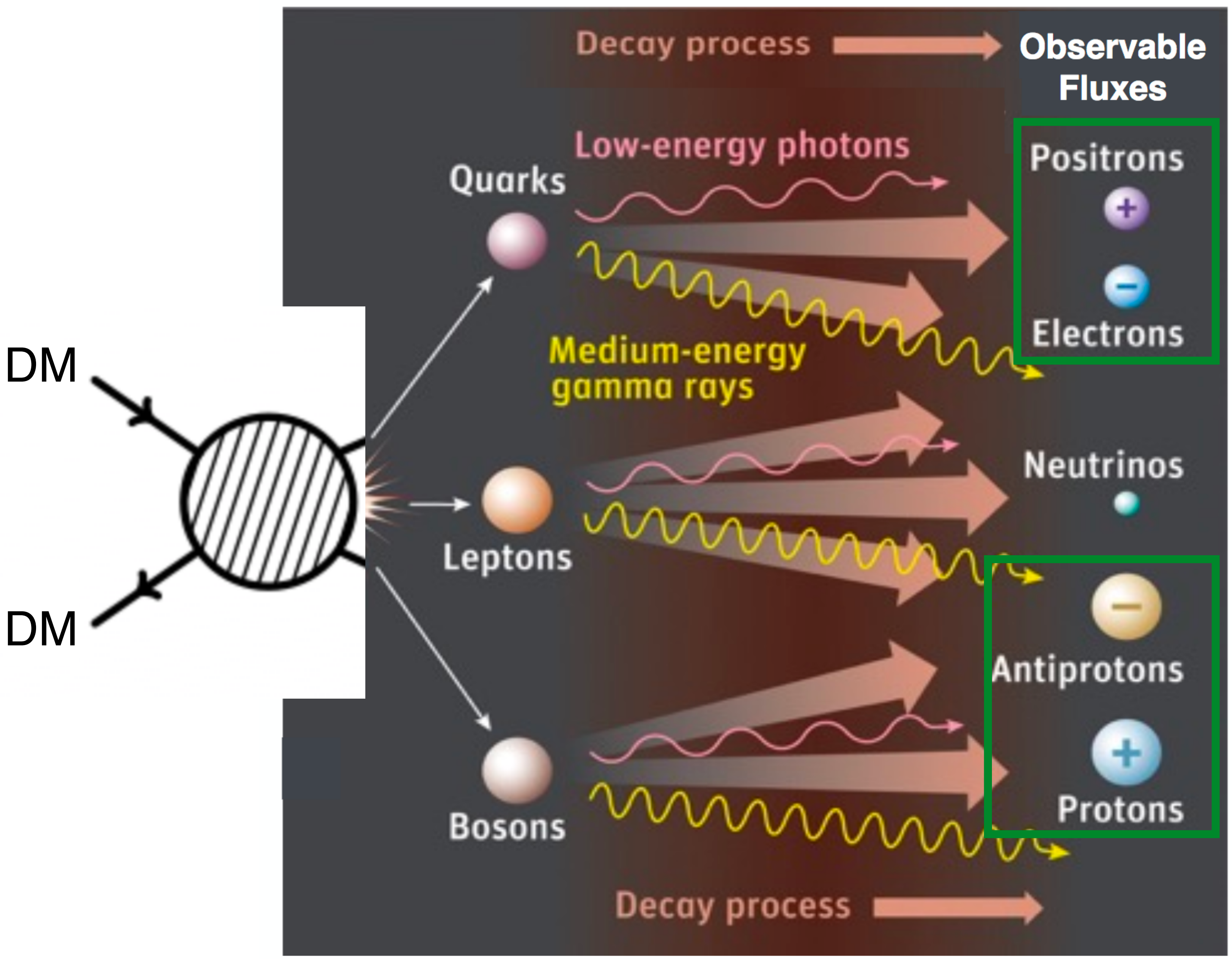
Indirect detection

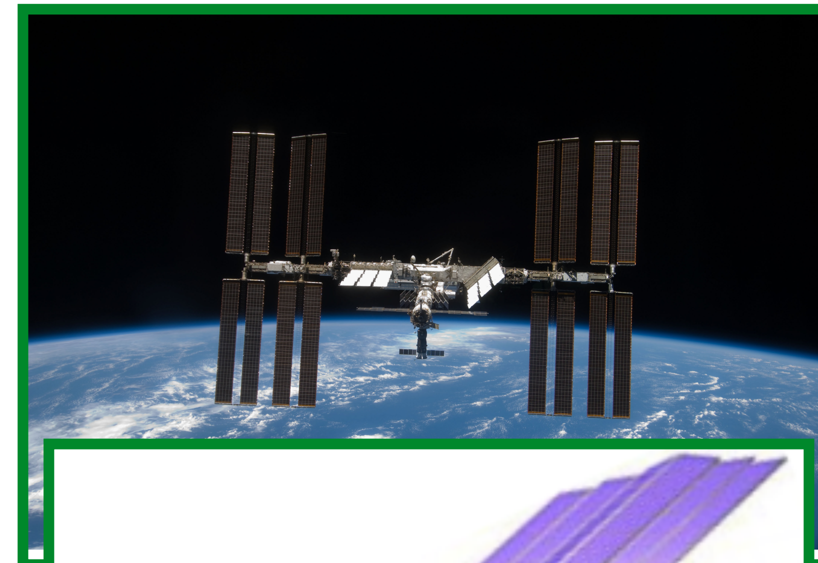
Prompt flux



Indirect detection

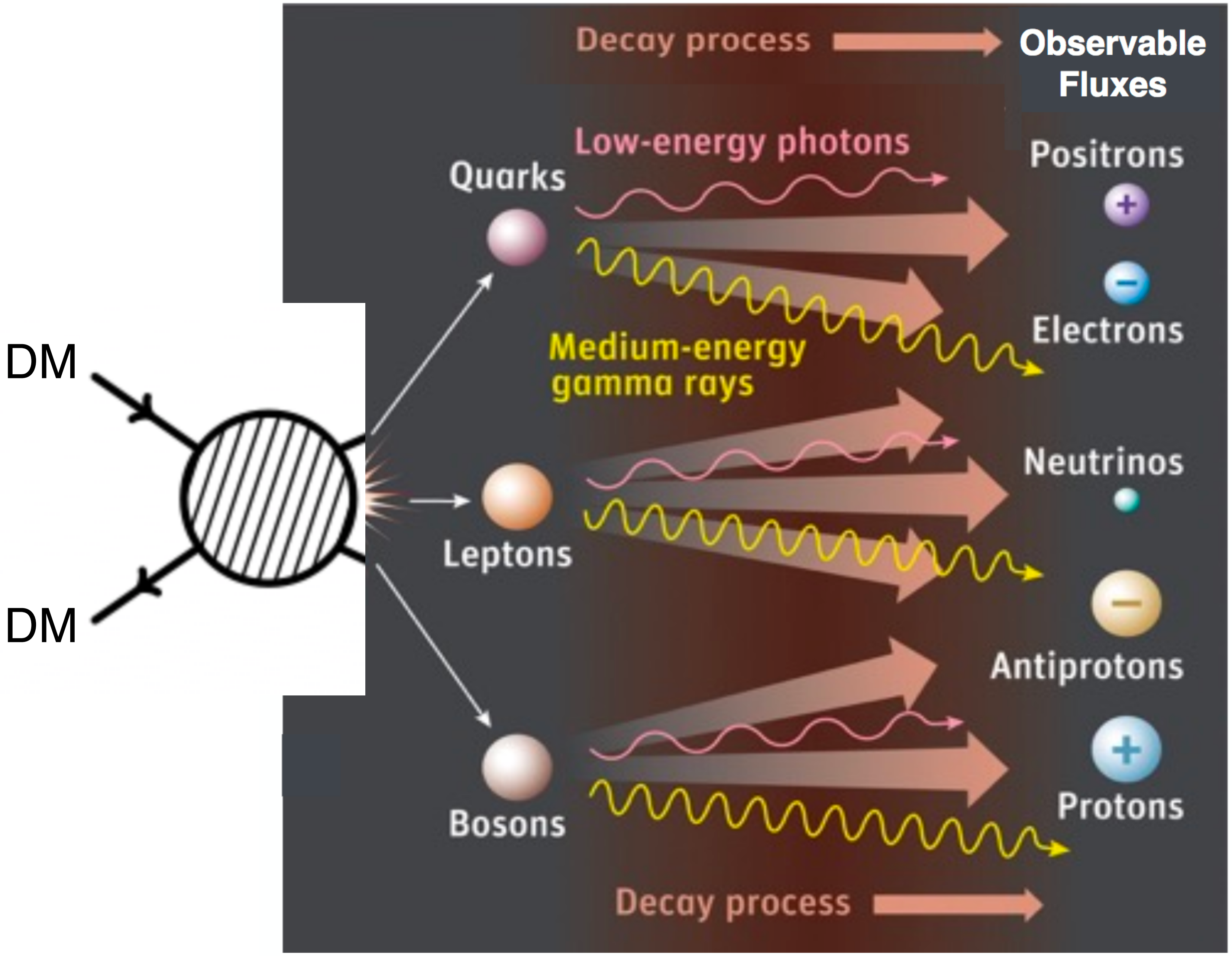
Prompt flux





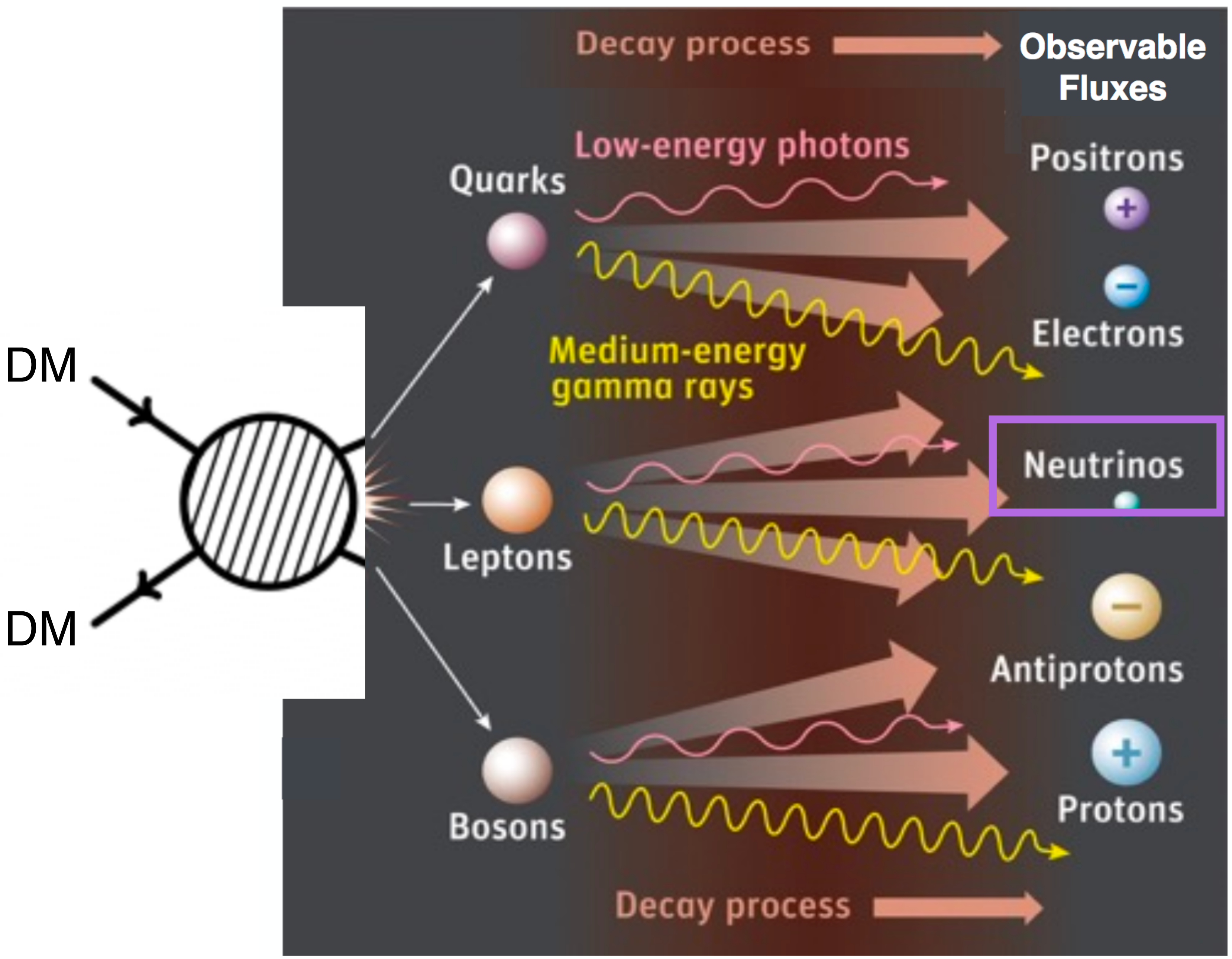
Indirect detection

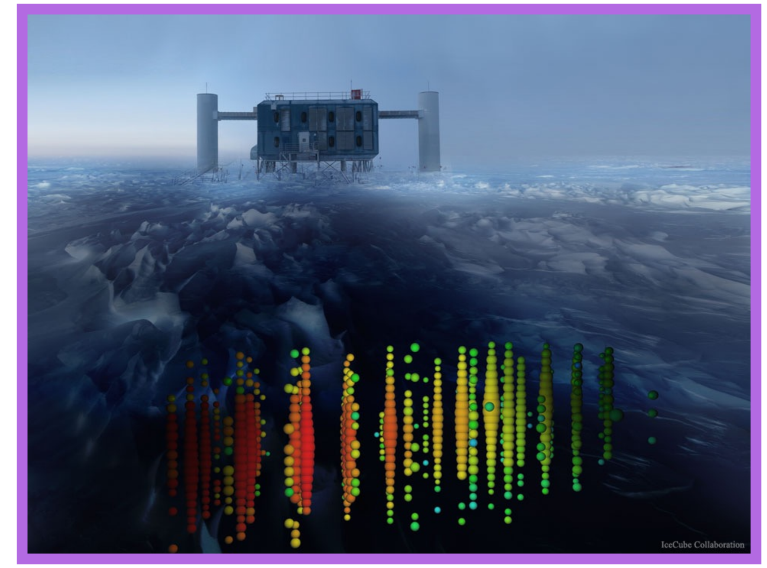
Prompt flux



Indirect detection

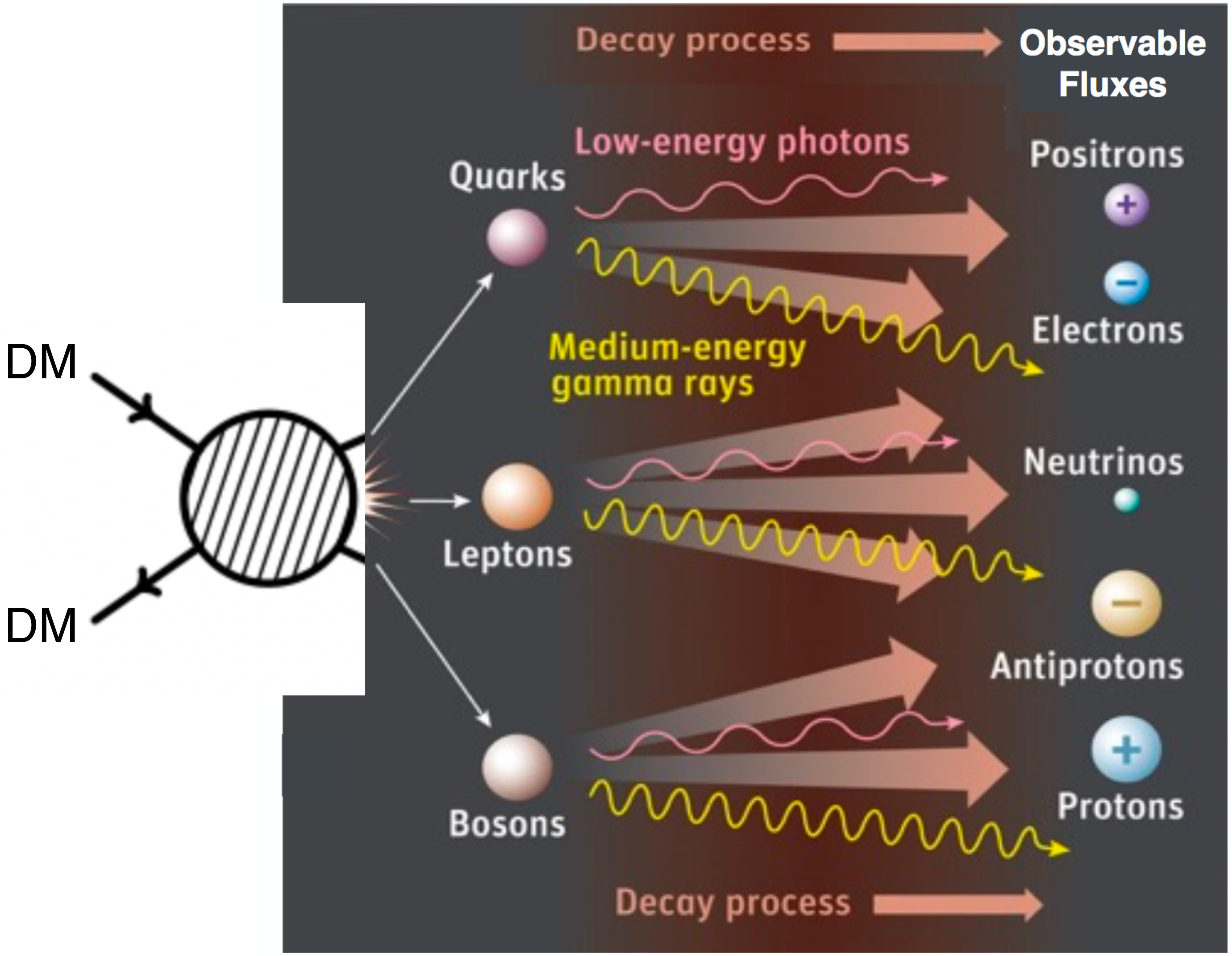
Prompt flux





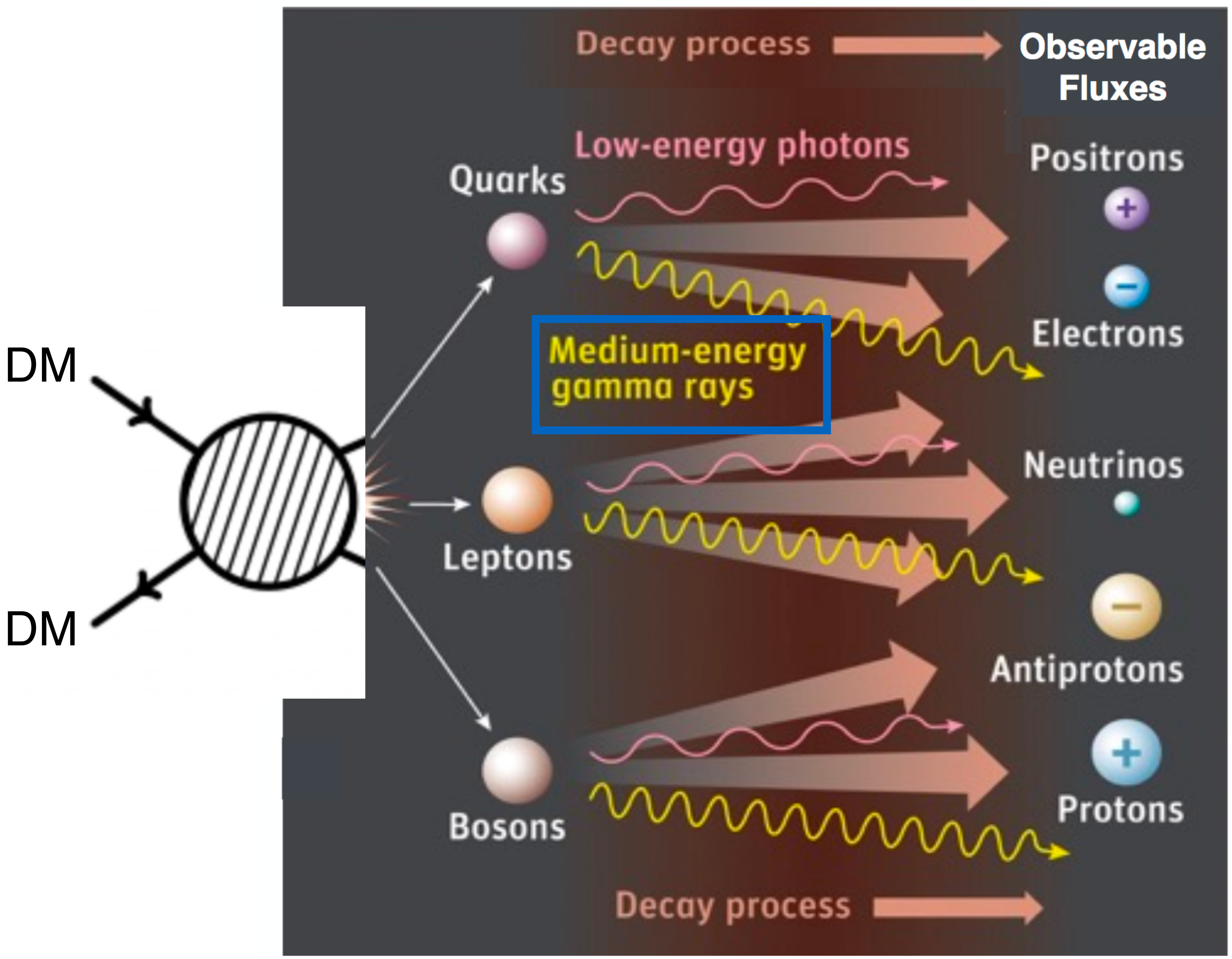
Indirect detection

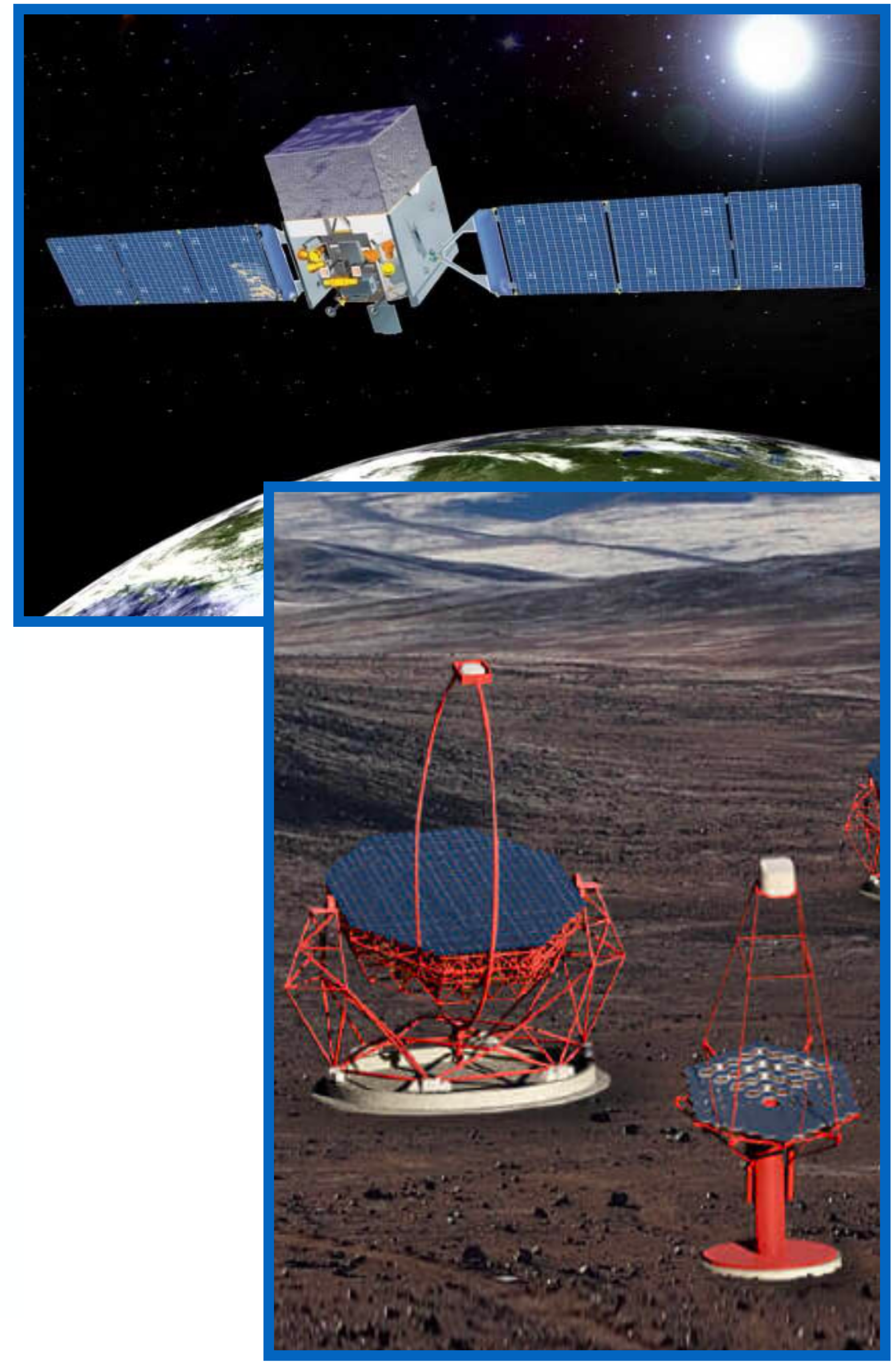
Prompt flux



Indirect detection

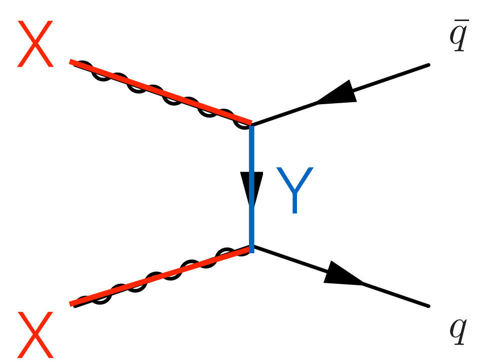
Prompt flux



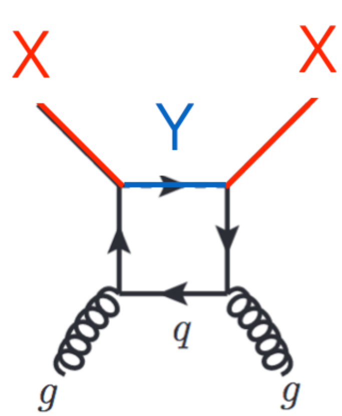


Dark matter annihilation in galactic halos at present time

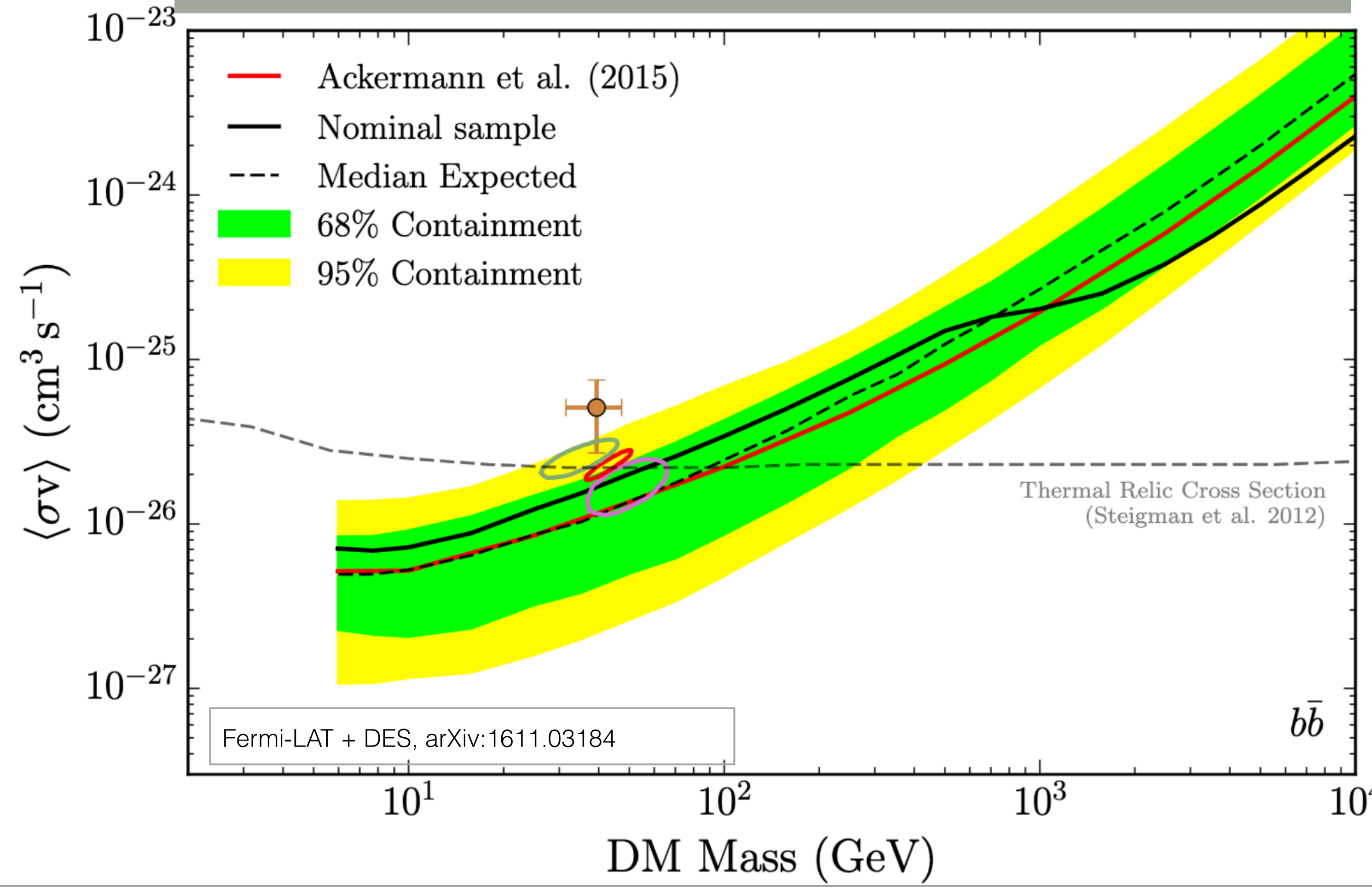
LO ANNIHILATION (DIRAC AND VECTORIAL DARK MATTER)



If quark is heavy (e.g. below top or b thresholds for models coupling to 2nd and 3rd gen)



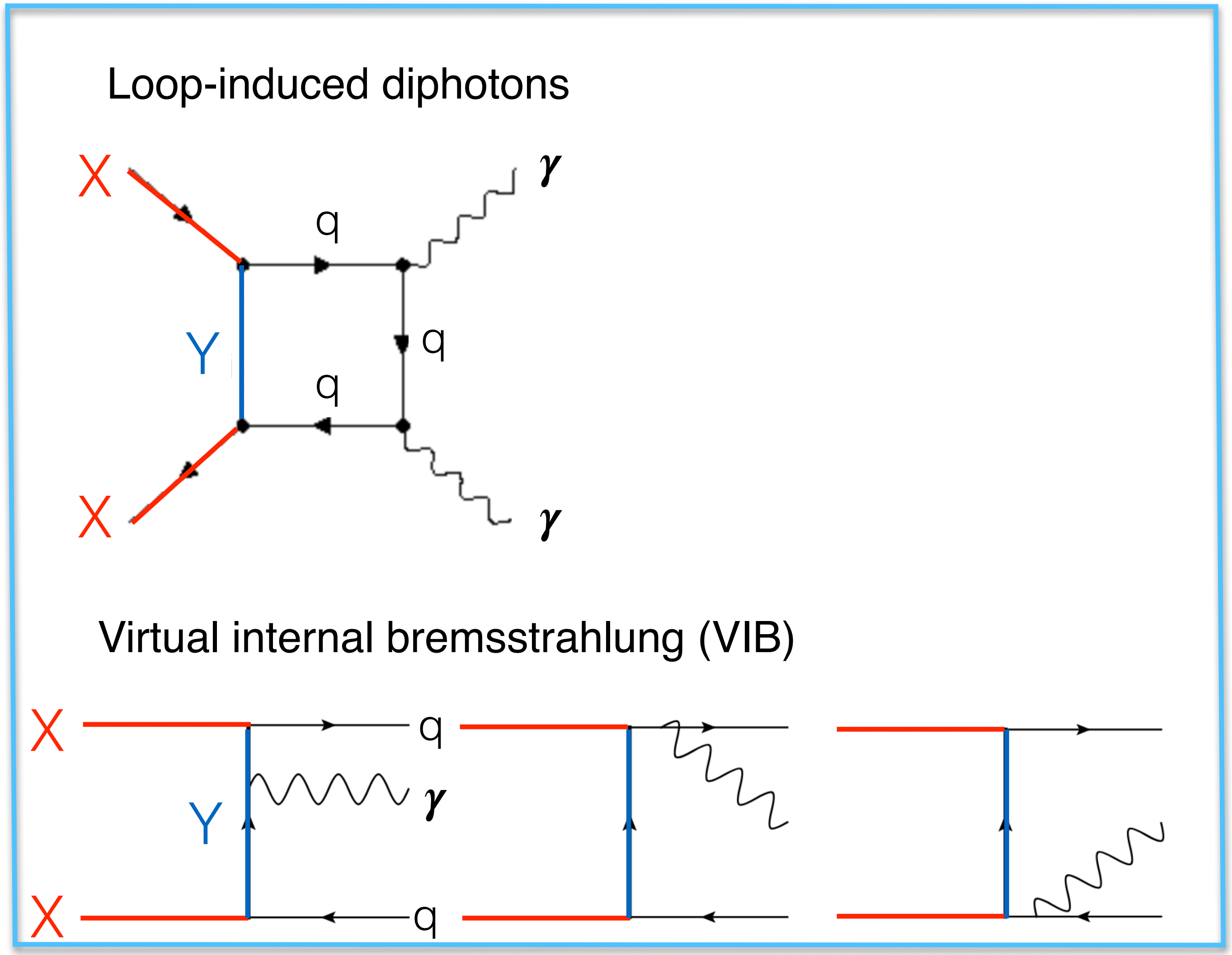
GAMMA-RAY BOUNDS FROM FERMI-LAT DWARF SPHEROIDAL GALAXIES ARE THE MOST CONSTRAINING



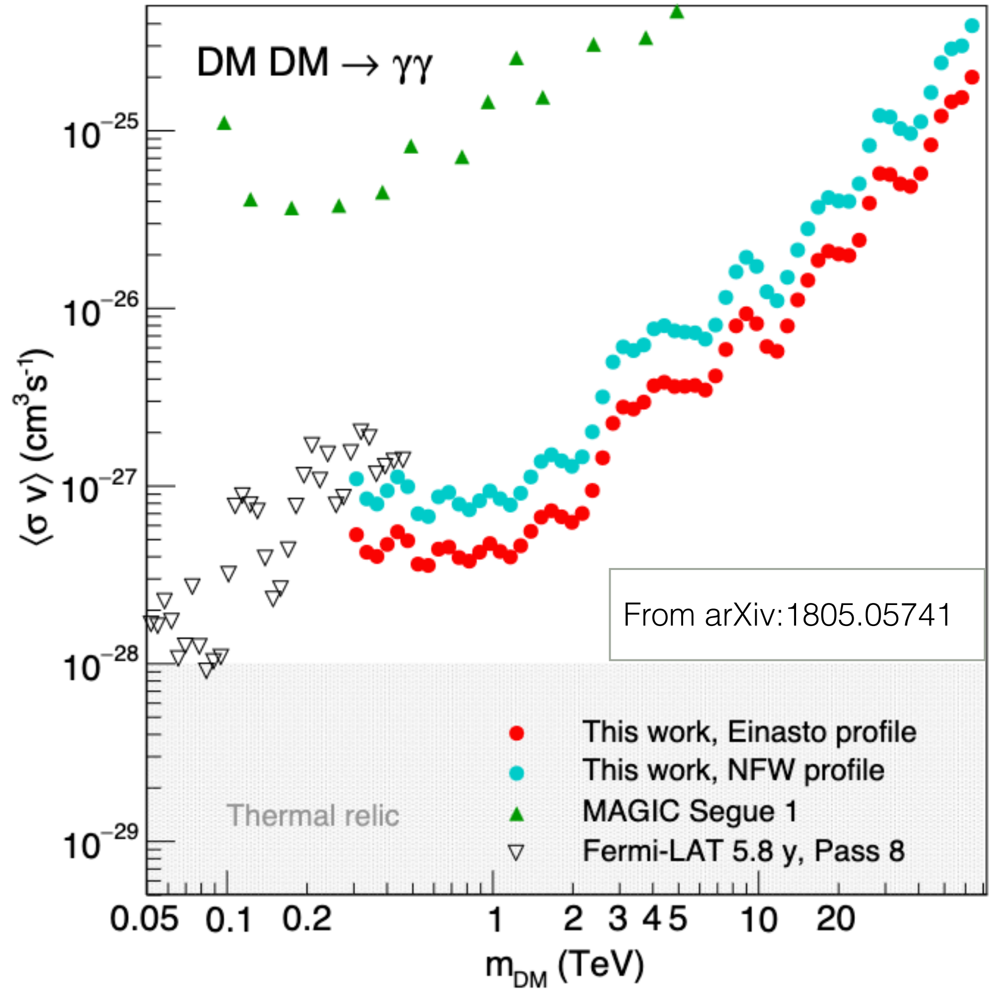
BOUNDS FROM FERMI-LAT DWARF SPHEROIDAL GALAXIES CAN BE COMPUTED AUTOMATICALLY WITHIN MADDM

Dark matter annihilation in galactic halos at present time

- **LO ANNIHILATION IS P-WAVE OR D-WAVE SUPPRESSED (MAJORANA OR SCALAR DARK MATTER)**
- **NLO PROCESSES UPLIFT THE SUPPRESSION AND PRODUCE A SHARP FEATURE IN THE GAMMA-RAY ENERGY SPECTRUM**



GAMMA LINE SEARCHES ARE THE MOST STRINGENT BOUNDS



Benchmark 1: coupling to u_R

Name	DM	Mediators	Parameters
S3M_uni	$\tilde{\chi}$	$\varphi_{Q_f}, \varphi_{u_f}, \varphi_{d_f}$	$M_\varphi, M_\chi, \lambda_\varphi$
S3D_uni	χ		
S3M_3rd	$\tilde{\chi}$	$\varphi_{Q_3}, \varphi_{u_3}, \varphi_{d_3}$	
S3D_3rd	χ		
S3M_uR	$\tilde{\chi}$	φ_{u_1}	
S3D_uR	χ		
F3S_uni	$\tilde{S}$	$\psi_{Q_f}, \psi_{u_f}, \psi_{d_f}$	$M_S, M_\psi, \hat{\lambda}_\psi$
F3C_uni	S		
F3S_3rd	$\tilde{S}$	$\psi_{Q_3}, \psi_{u_3}, \psi_{d_3}$	
F3C_3rd	S		
F3S_uR	$\tilde{S}$	ψ_{u_1}	
F3C_uR	S		
F3V_uni	$\tilde{V}_\mu$	$\psi_{Q_f}, \psi_{u_f}, \psi_{d_f}$	$M_V, M_\psi, \hat{\lambda}_\psi$
F3W_uni	V_μ		
F3V_3rd	$\tilde{V}_\mu$	$\psi_{Q_3}, \psi_{u_3}, \psi_{d_3}$	
F3W_3rd	V_μ		
F3V_uR	$\tilde{V}_\mu$	ψ_{u_1}	
F3W_uR	V_μ		

We consider all models coupling to u_R quark
6 in total
(M_X, M_Y, λ)

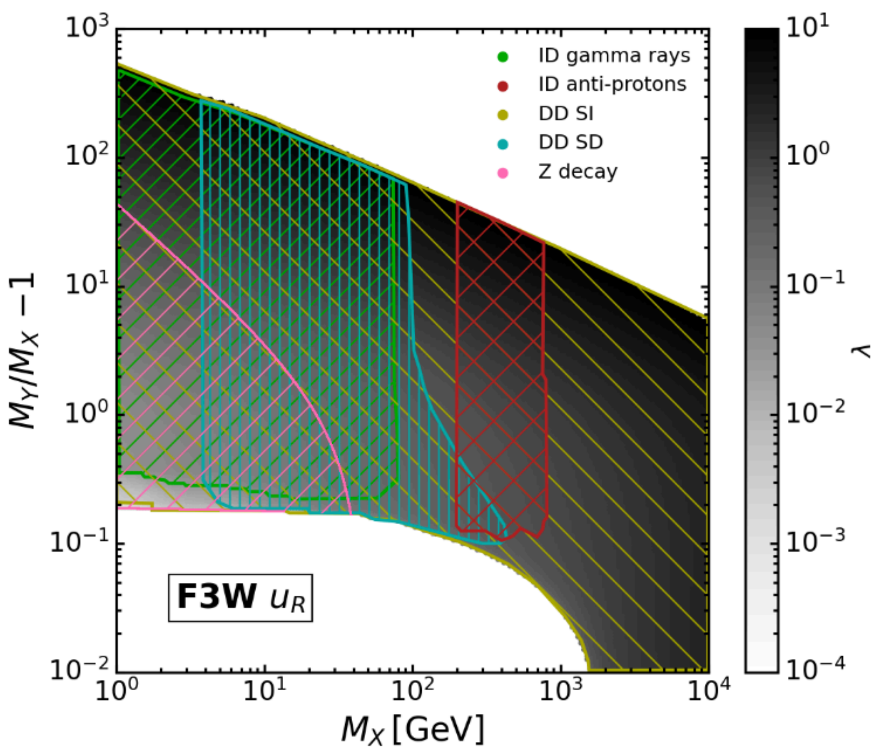
Fermionic DM (Majorana and Dirac) and scalar mediator

Scalar DM (real and complex) and fermionic mediator

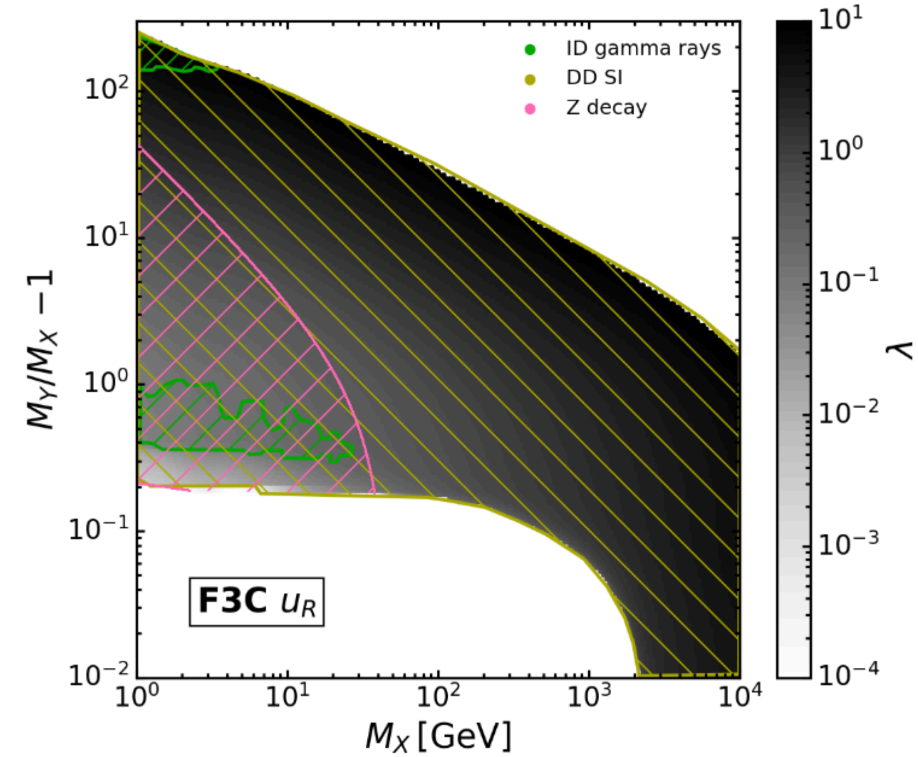
Vector DM (real and complex) and fermionic mediator

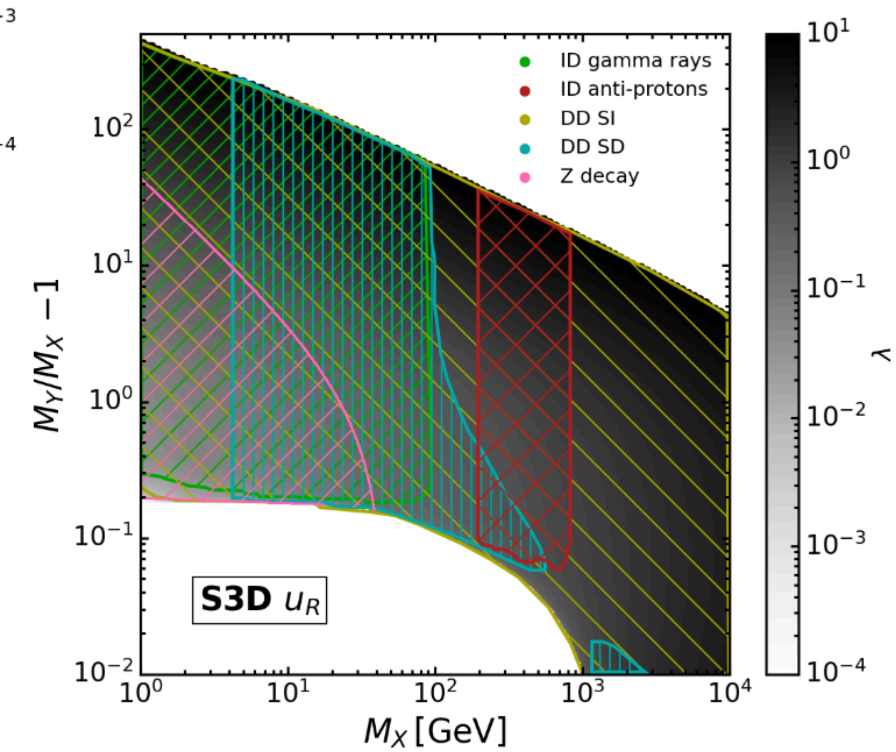
Benchmark 1: coupling to u_R complex case

From arXiv:2307.10367



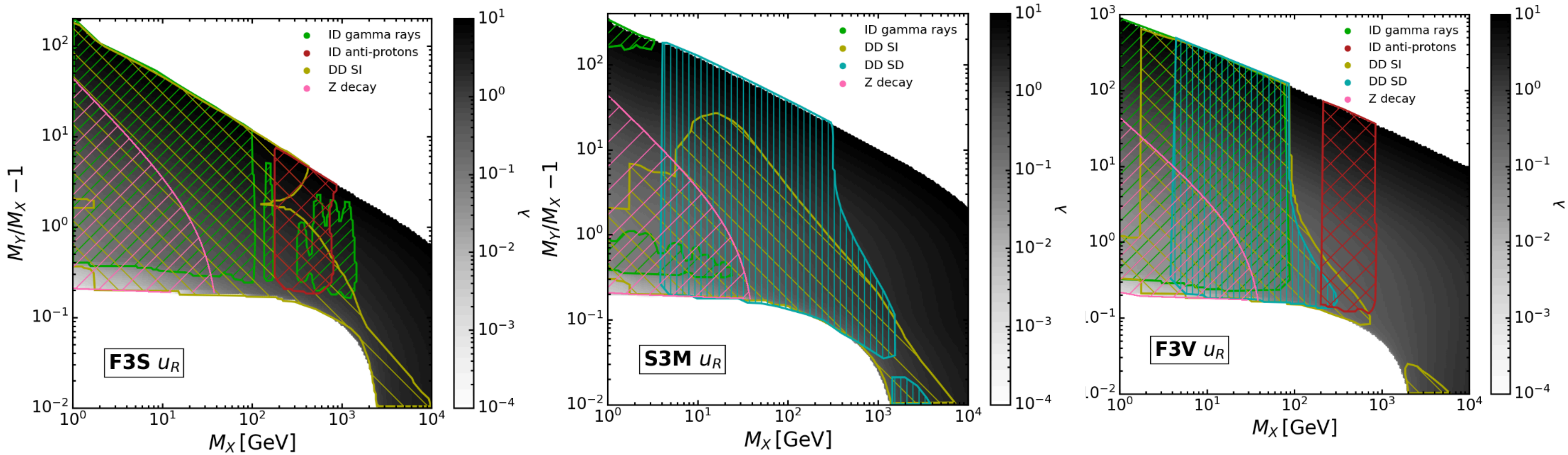
ASSUMING WIMP SCENARIO AND CORRECT RELIC DENSITY VIA FO ALL COMPLEX MODELS ARE EXCLUDED UP TO 10 TEV BY DIRECT DETECTION !





FREEZE-IN REGION AND COMPRESSED SPECTRA TO BE INVESTIGATED STILL…

Benchmark 1: coupling to u_R real case



ASSUMING WIMP SCENARIO AND CORRECT RELIC DENSITY VIA FO COSMOLOGY EXCLUDES A LOT BUT STILL VIABLE BENCHMARKS

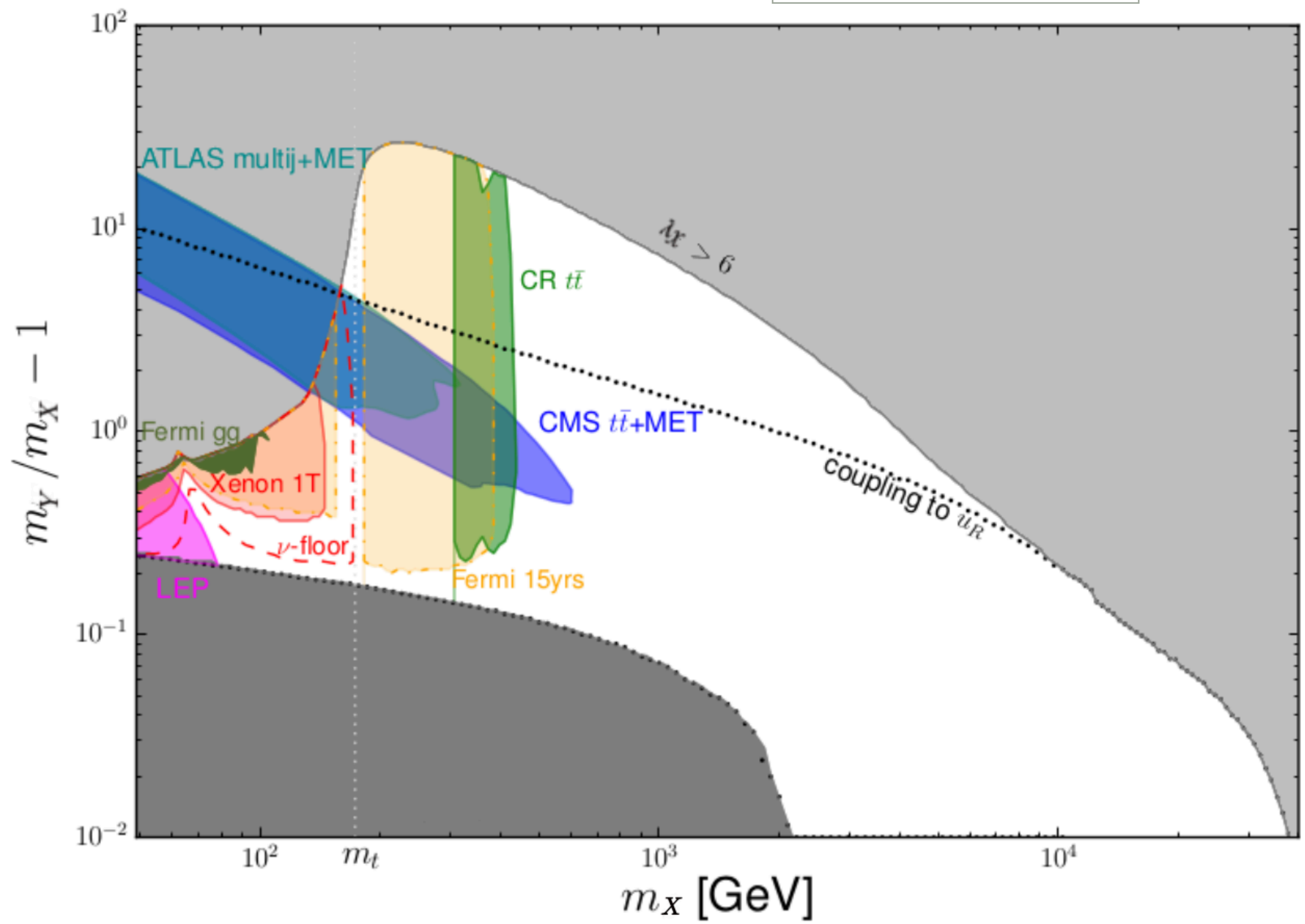
FREEZE-IN REGION AND COMPRESSED SPECTRA TO BE INVESTIGATED STILL…

From arXiv:2307.10367

Benchmark 2: coupling to t_R

Real scalar particle as X and fermionic particle as Y
(M_X, M_Y, λ)

From arXiv:1804.05068



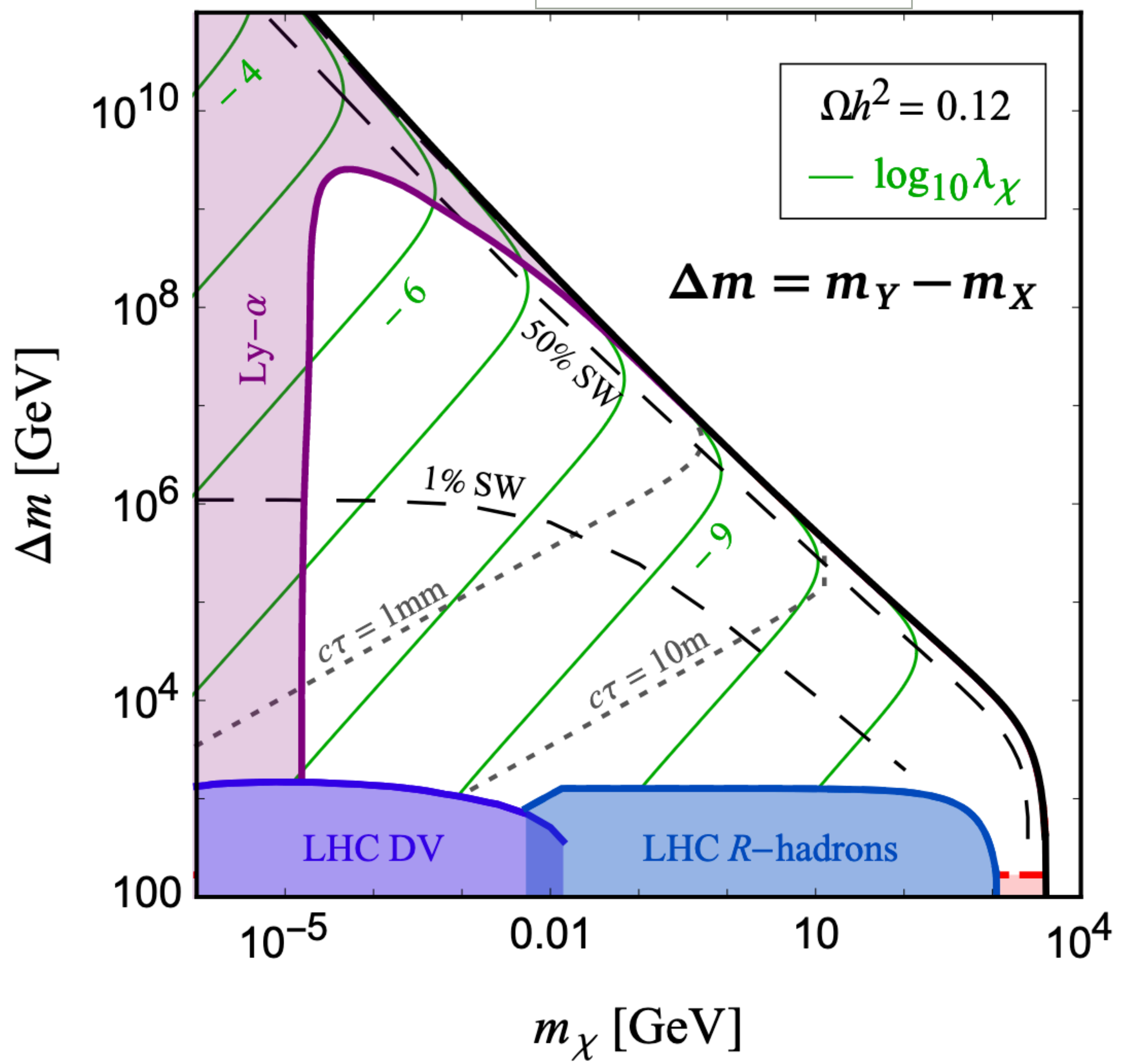
- **BEHAVIOR IS SIMILAR TO THE CASE OF U_R**
- **NON NEGLIGIBLE MASS OF THE TOP IS RELEVANT AND NEED A CAREFUL TREATMENT**
- **COMPLEMENTARITY OF ASTROPARTICLE AND COLLIDER SEARCHES**

Benchmark 2: coupling to t_R for freeze-in and superWIMP

Majorana particle as X and scalar particle as Y
(M_X, M_Y, λ)

- WIDE RANGE OF DM MASSES CAN BE CONSIDERED
- LOW MASSES ARE CONSTRAINED BY COSMOLOGY
- COMPRESSED SPECTRA CONSTRAINED BY DISPLACED VERTICES AND R-HADRONS
- NICE COMPLEMENTARITY
- WIDE VIABLE REGION (NO DD OR ID BOUND)

From arXiv:2111.09321



Summary

DARK MATTER CANDIDATES ARISING FROM SIMPLIFIED AND MINIMAL T-CHANNEL MODELS ARE PARTICULAR ATTRACTIVE BECAUSE OF THEIR PREDICTIVITY:

- IF CONSIDERED AS WIMPS THEY ARE PRETTY CONSTRAINED BY INDIRECT AND DIRECT SEARCHES OF DARK MATTER;
- MODELS COUPLING TO U AND D ARE MORE CONSTRAINED (COMPLEX CANDIDATES ARE BASICALLY EXCLUDED)
- MODELS COUPLING TO 2ND AND 3RD GEN ARE LESS CONSTRAINED BY DIRECT DETECTION
- PHENO OF RELIC AND INDIRECT DETECTION DO NOT STRONGLY DEPEND ON THE QUARK FLAVOR (BESIDES MASS EFFECTS)

- Models beyond the minimal version and/or theoretical complete models feature enlarged parameter space, specific signatures, …;
- Freeze-in, superWIMP, conversion driven freeze-out are other mechanisms that shape LLP regions and/or very compressed spectra: different regions and masses to explore yet;
- A non-standard cosmological history can change the model parameter space and open up new regions;
- Much more in the white paper to appear, stay tuned!

Back up slides

Bound states and Sommerfeld enhancement (from arXiv:2203.04326)

SOMMERFELD ENHANCEMENT

$$\sigma_{\mathrm{SE},[\mathbf{R}]} v_{\mathrm{rel}} = c_{[\mathbf{R}]} S_{0,[\mathbf{R}]}\, \sigma_0,$$

$$V(r)_{\mathbf{3}\otimes\bar{\mathbf{3}}} = \begin{cases} -\frac{4}{3}\frac{\alpha_s}{r} & [\mathbf{1}] \\ +\frac{1}{6}\frac{\alpha_s}{r} & [\mathbf{8}] \end{cases} \quad ; \quad V(r)_{\mathbf{3}\otimes\mathbf{3}} = \begin{cases} -\frac{2}{3}\frac{\alpha_s}{r} & [\bar{\mathbf{3}}] \\ +\frac{1}{3}\frac{\alpha_s}{r} & [\mathbf{6}] \end{cases}$$

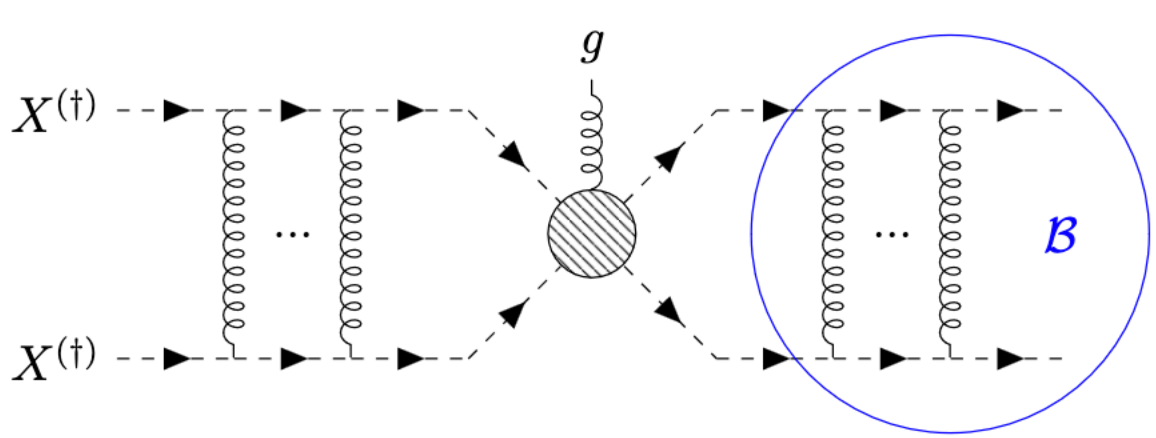
$$\sigma_{\mathbf{3}\otimes\bar{\mathbf{3}}\to gg} v_{\mathrm{rel}} = \sigma_{\mathbf{3}\otimes\bar{\mathbf{3}}\to gg,0}\left(\frac{2}{7}S_{0,[\mathbf{1}]} + \frac{5}{7}S_{0,[\mathbf{8}]}\right),$$

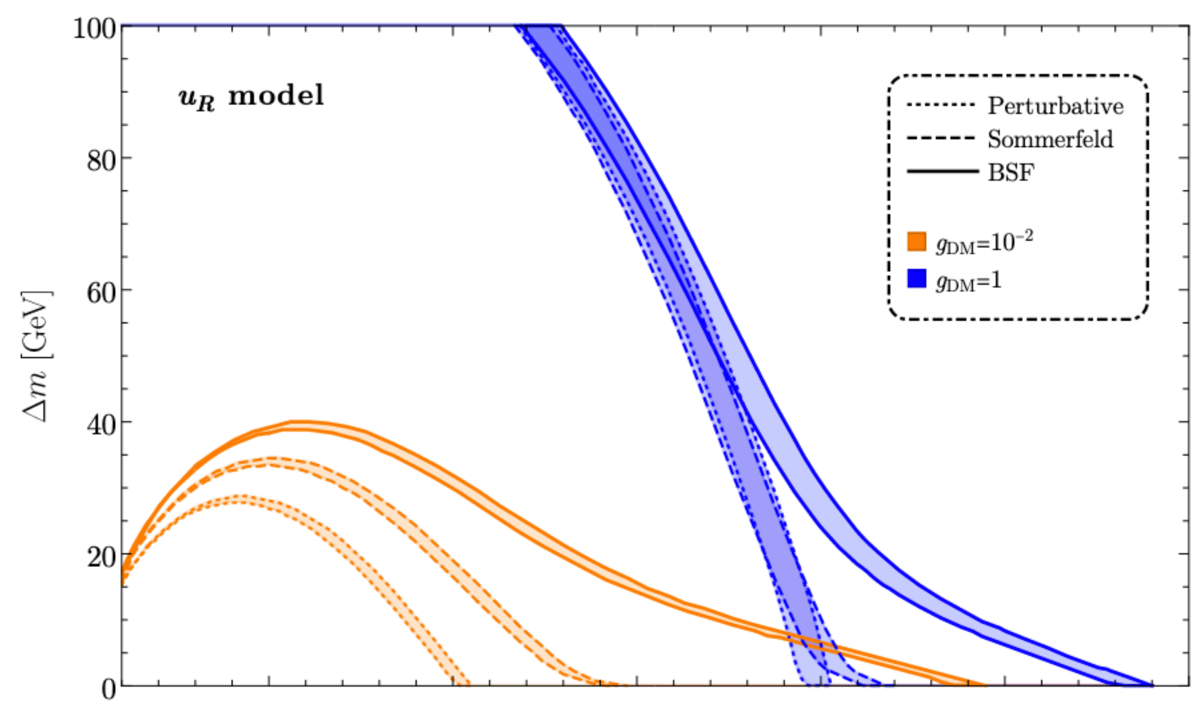
$$\sigma_{\mathbf{3}\otimes\bar{\mathbf{3}}\to q\bar{q}} v_{\mathrm{rel}} = \sigma_{\mathbf{3}\otimes\bar{\mathbf{3}},0}\left(f_{[\mathbf{1}]}(g_s, g_{\mathrm{DM}})S_{0,[\mathbf{1}]} + f_{[\mathbf{8}]}(g_s, g_{\mathrm{DM}})S_{0,[\mathbf{8}]}\right),$$

$$\sigma_{\mathbf{3}\otimes\mathbf{3}\to qq} v_{\mathrm{rel}} = \sigma_{\mathbf{3}\otimes\mathbf{3}\to qq,0} S_{0,[\mathbf{6}]},$$

$$\sigma_{\mathbf{3}_i\otimes\mathbf{3}_j\to q_i q_j} = \sigma_{\mathbf{3}_i\otimes\mathbf{3}_j\to q_i q_j,0}\left(\frac{1}{3}S_{0,[\bar{\mathbf{3}}]} + \frac{2}{3}S_{0,[\mathbf{6}]}\right).$$

EXAMPLE OF BOUND STATE FORMATION





Lyman-alpha bounds

FI AND SW (NON-THERMAL) CAN BE PRODUCED WITH A CERTAIN BOOST AND AFFECT STRUCTURE FORMATION

BOUNDS FROM WARM DARK MATTER (THERMAL) CAN BE TRANSLATED INTO FI AND SW TERMS

$$m_X \gtrsim \begin{cases} 15\,\text{keV} \times \left(\dfrac{106.75}{g_*(T_{\text{FI}})}\right)^{1/3} & \text{for FI through decays,} \\ 3.8\,\text{GeV} \times \left(R_\Gamma^{\text{SW}}/10^{-12}\right)^{-1/2} \times \left(\dfrac{106.75}{g_*(T_{\text{SW}})}\right)^{1/3} & \text{for SW,} \end{cases}$$