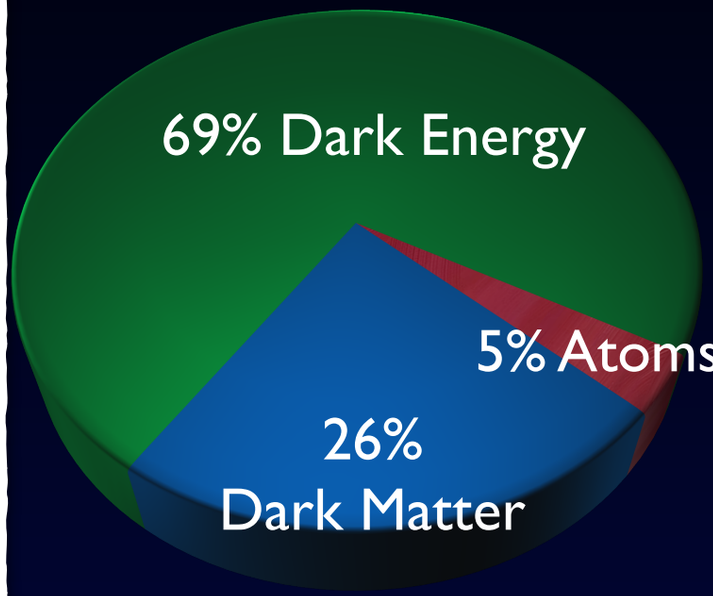
Implications of DM search results: How to save the WIMP

Thomas Schwetz

Lepton-Photon 2017
Sun Yat-Sen University, Guangzhou, China

Dark matter is needed!

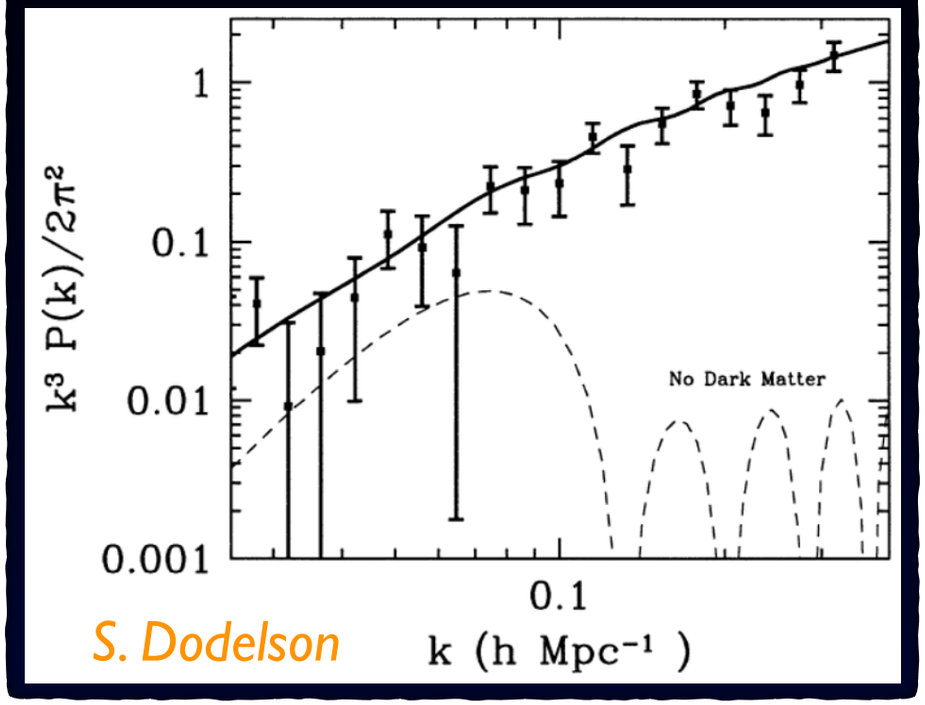
ΛCDM fit to CMB + BAO



$$\Omega_B h^2 = 0.02230 \pm 0.00014$$
$$\Omega_C h^2 = 0.1188 \pm 0.0010$$
$$\Omega_\Lambda = 0.6911 \pm 0.0062$$
$$h = 0.6774 \pm 0.0046$$

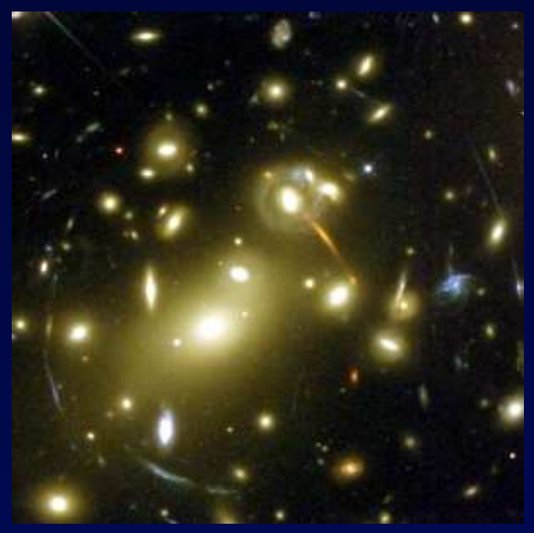
1502.01589

need DM to grow structure

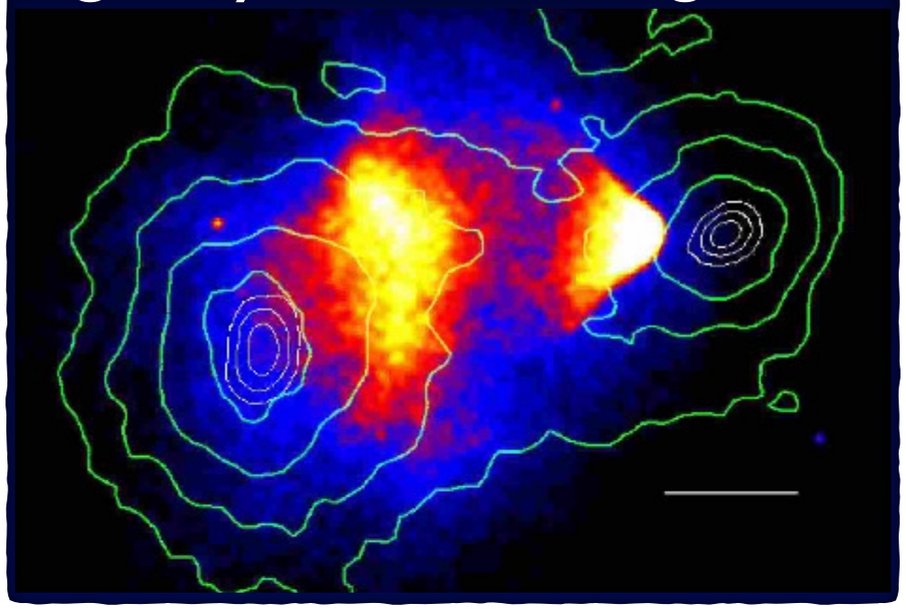


S. Dodelson

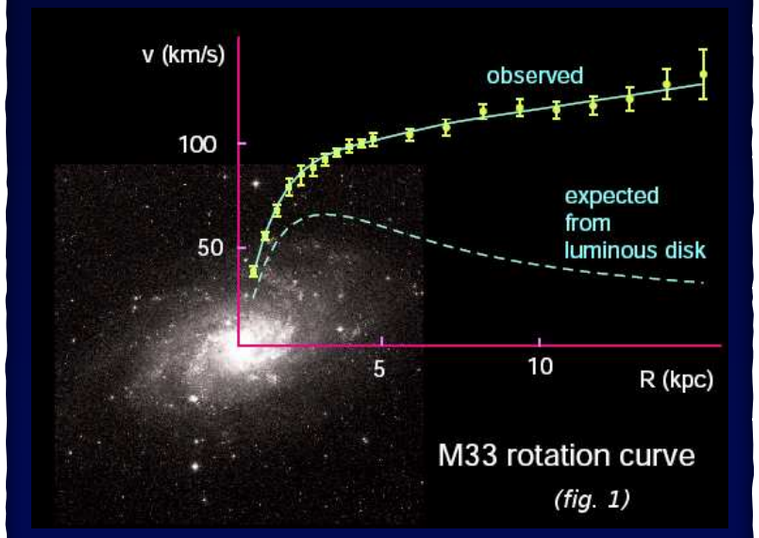
gravitational lensing



galaxy cluster mergers



rotation curves



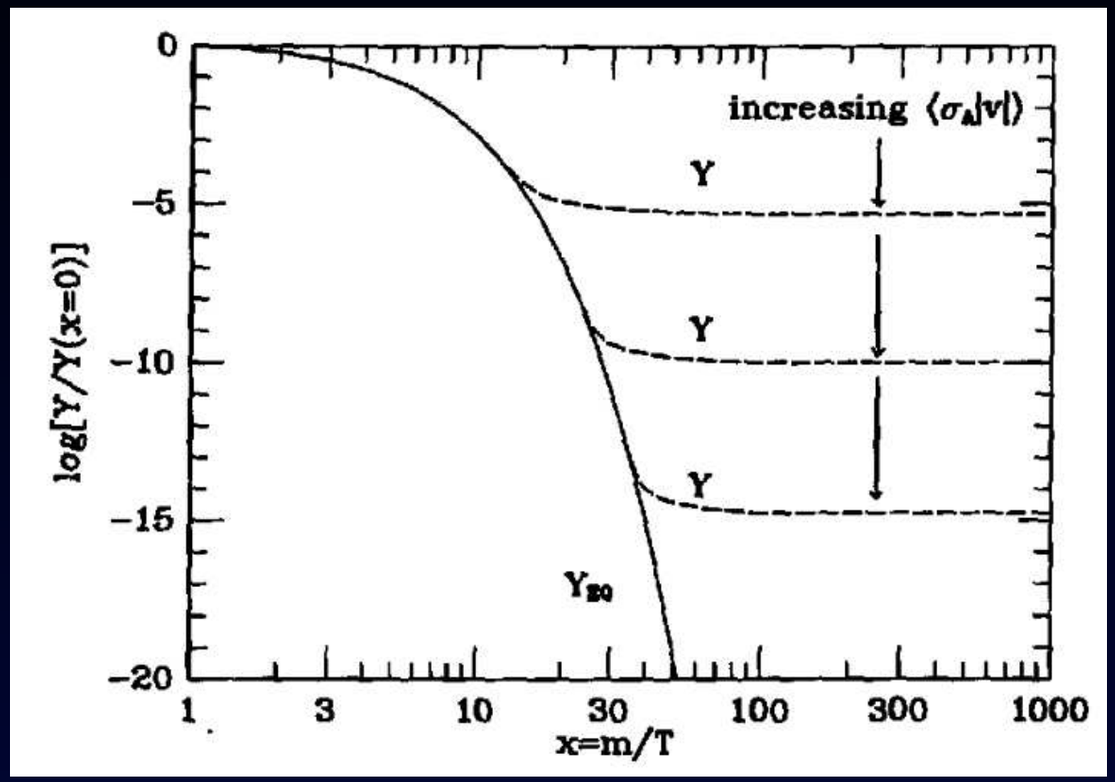
Challenge for particle physics

- within the Standard Model there is no suitable particle to provide the DM
  → need new particle(s)

- Why is it so abundant?
- Why is it (quasi) stable?
- Is it elementary or composite?
- Is there a „dark sector“?

- many possible candidates
- this talk focus on WIMP candidates

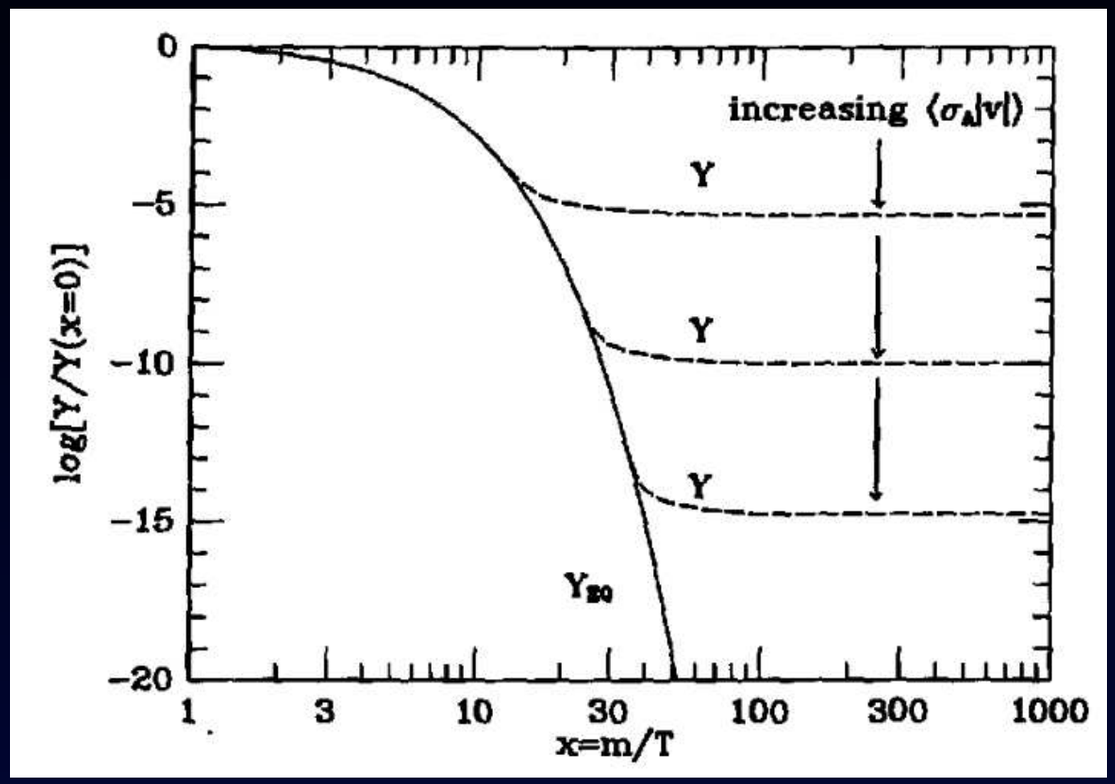
The WIMP hypothesis: thermal freeze-out



$$\Omega_{\rm DM} \approx \frac{2\times 10^{-37}{\rm cm}^2}{\langle \sigma_{\rm annih} v\rangle} \approx 0.23$$

Lee, Weinberg, 1977
Bernstein, Brown, Feinberg, 1985
Scherrer, Turner, 1986

The WIMP hypothesis: thermal freeze-out



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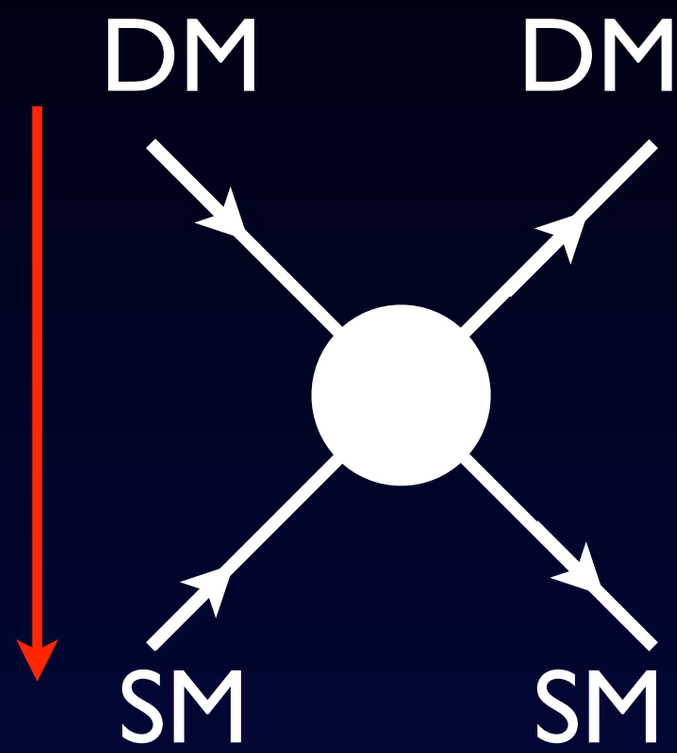
"typical" annihilation cross section:

$$\langle \sigma_{\rm annih} v\rangle \sim \frac{g^4}{2\pi m^2} \simeq 6\times 10^{-37}{\rm cm}^2 \left(\frac{g}{0.1}\right)^4 \left(\frac{m}{100\,{\rm GeV}}\right)^{-2}$$

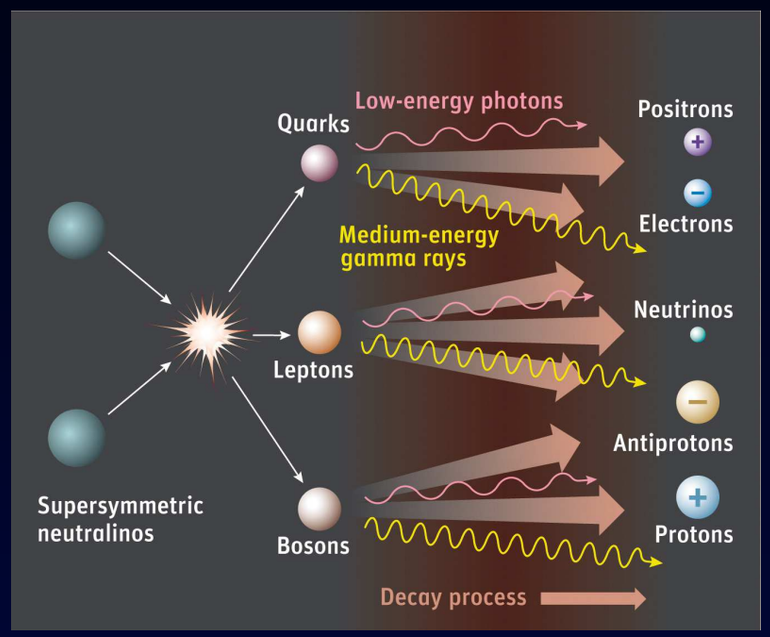
- "Weakly Interacting Massive Particle" (WIMP)
- relation with new physics at the TeV scale

WIMP searches

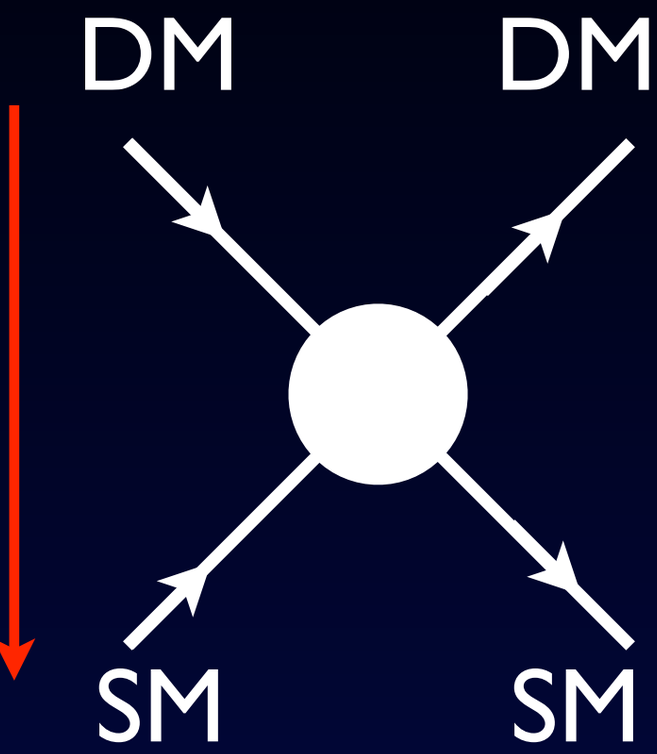


WIMP searches

indirect detection



PAMELA, FERMI, AMS-2, HESS, IceCube



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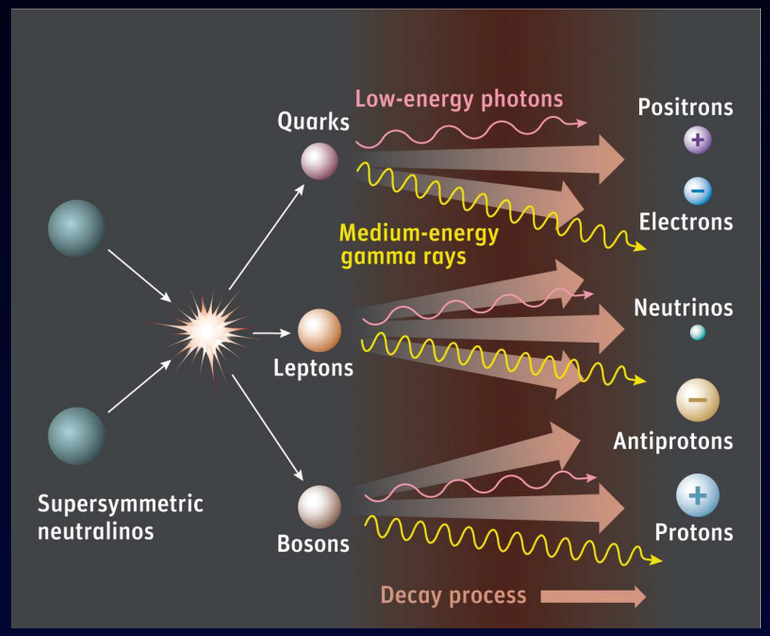

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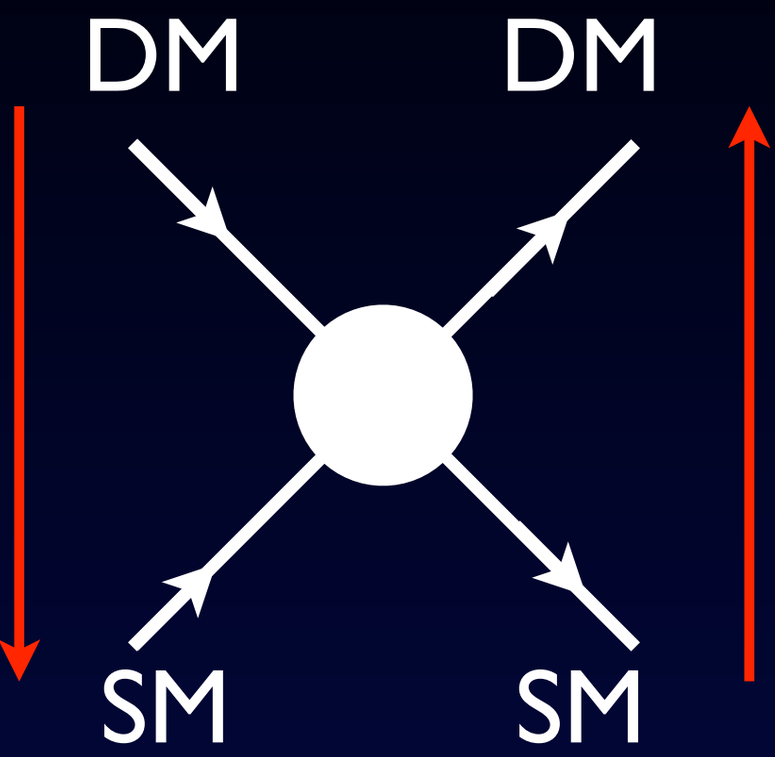
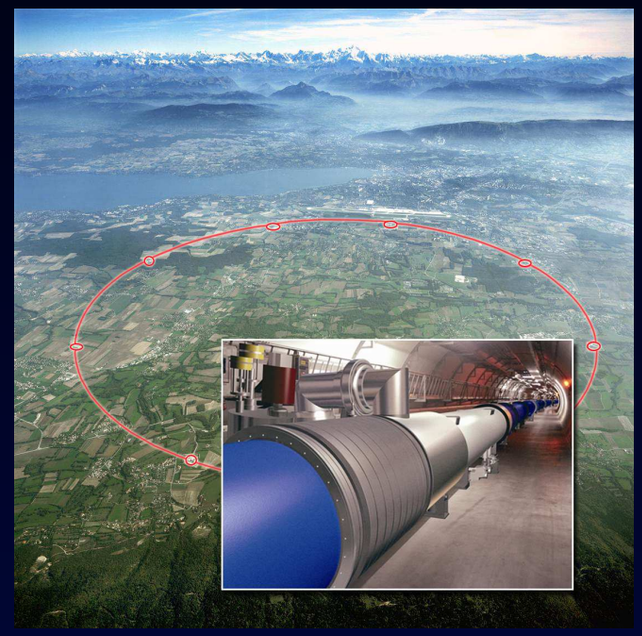


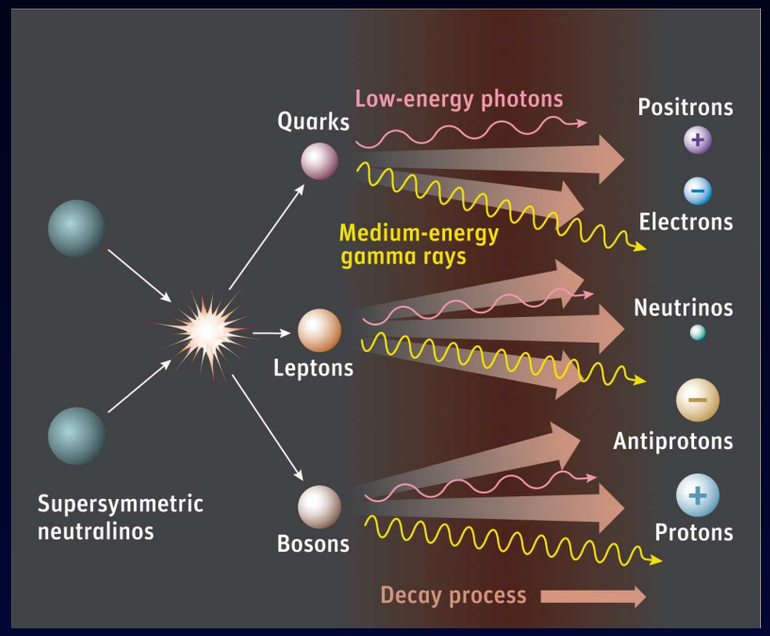
accelerators



LHC

WIMP searches

indirect detection



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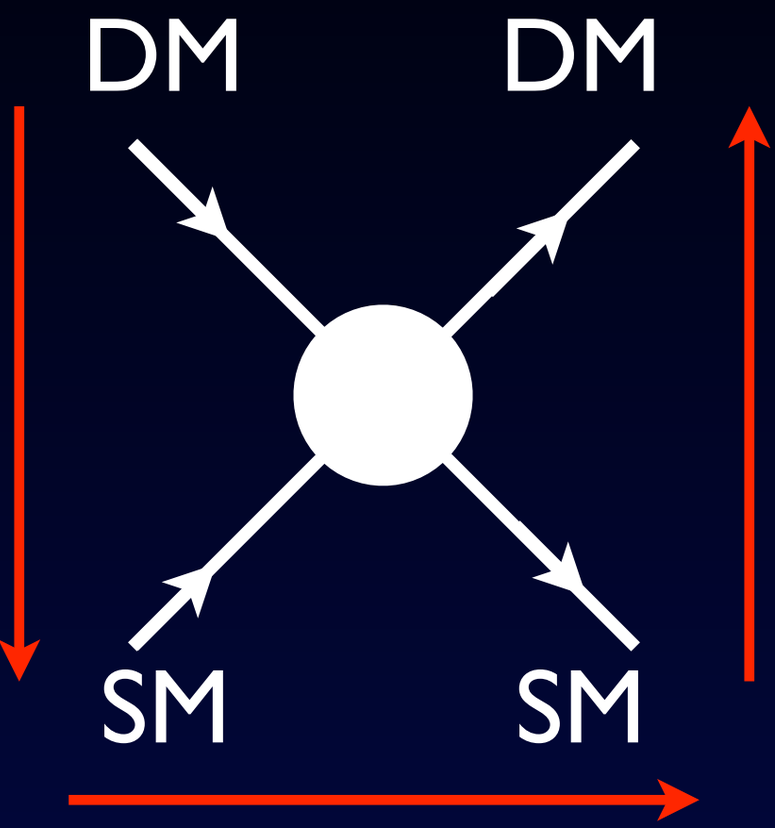
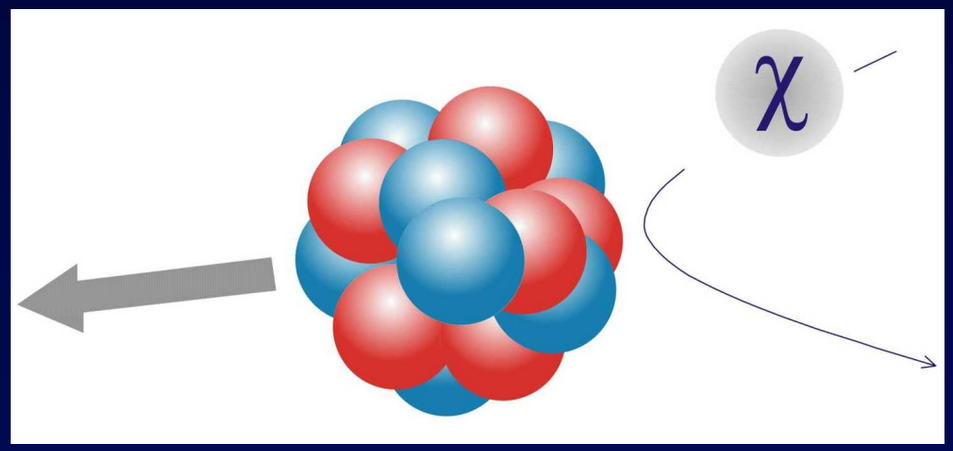
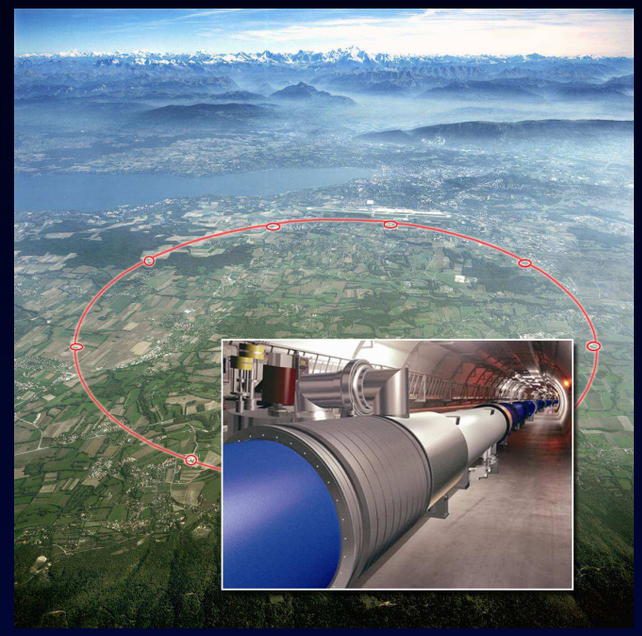


direct detection



XENON, LUX, PANDA-X, CDMS, Edelweiss, CRESST, PICASSO, COUPP,...

accelerators



LHC

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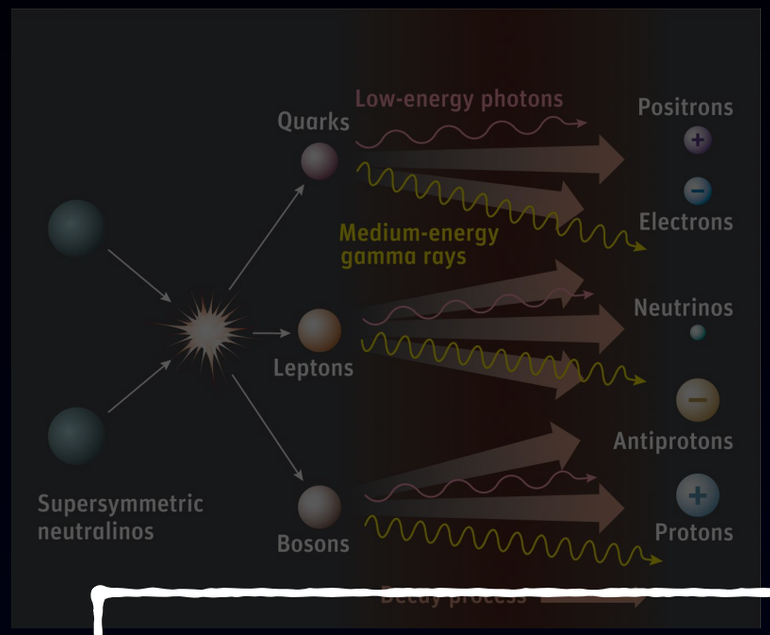
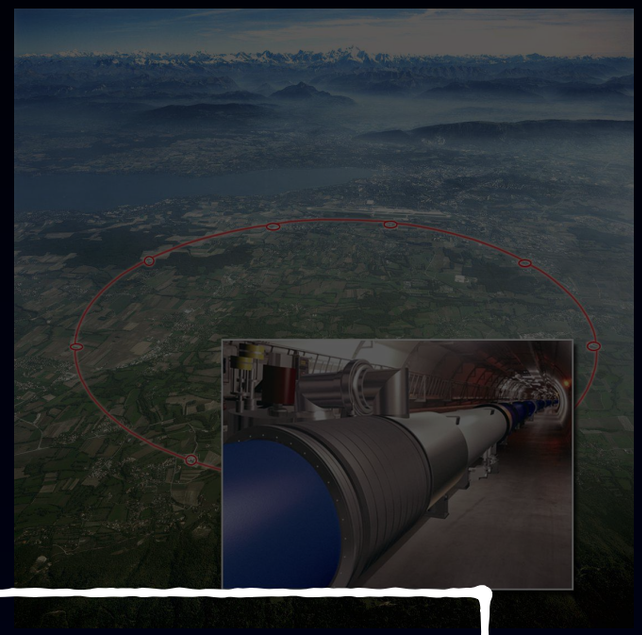


PAMELA, FERMI, MAGIC, HESS, IceCube

accelerators



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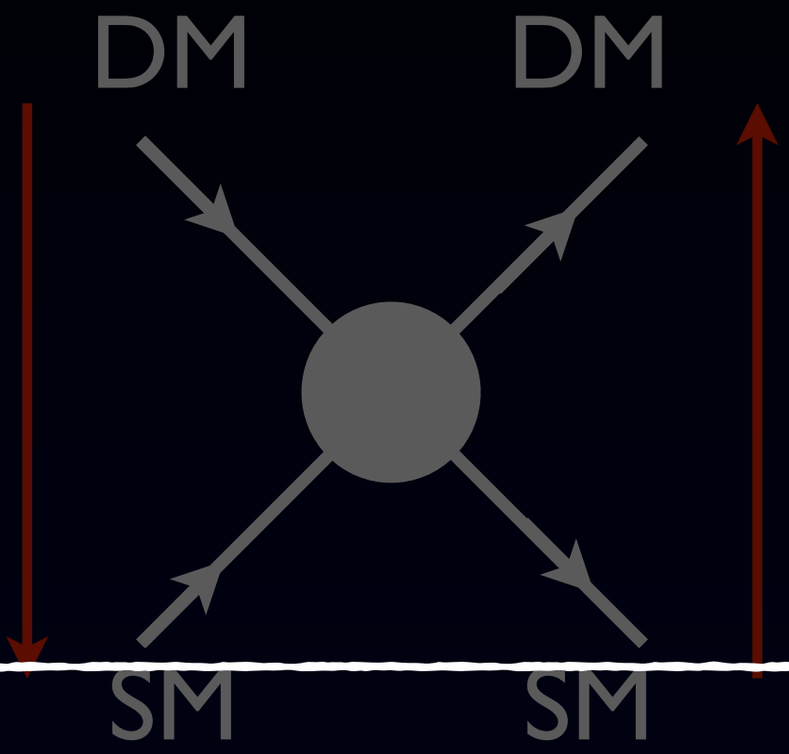

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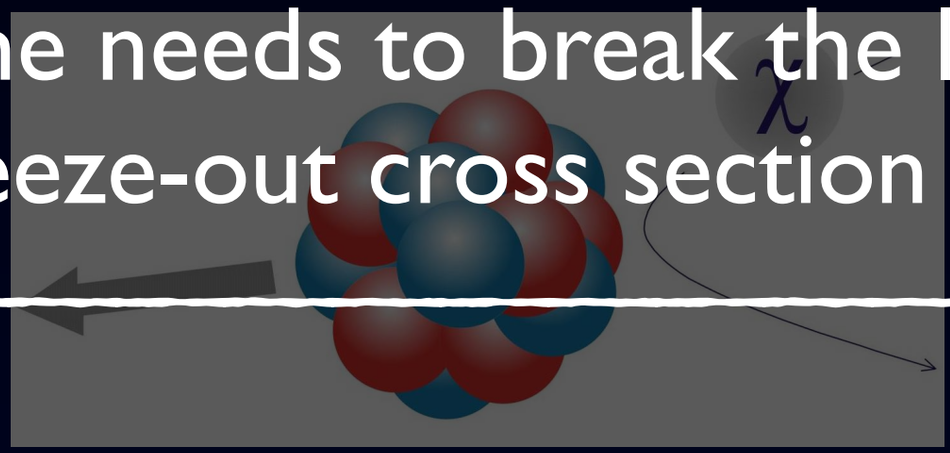
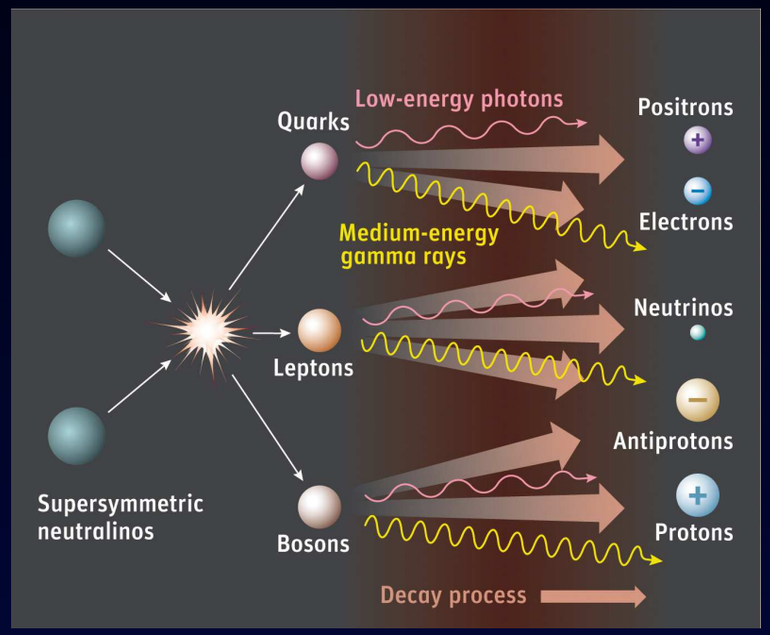


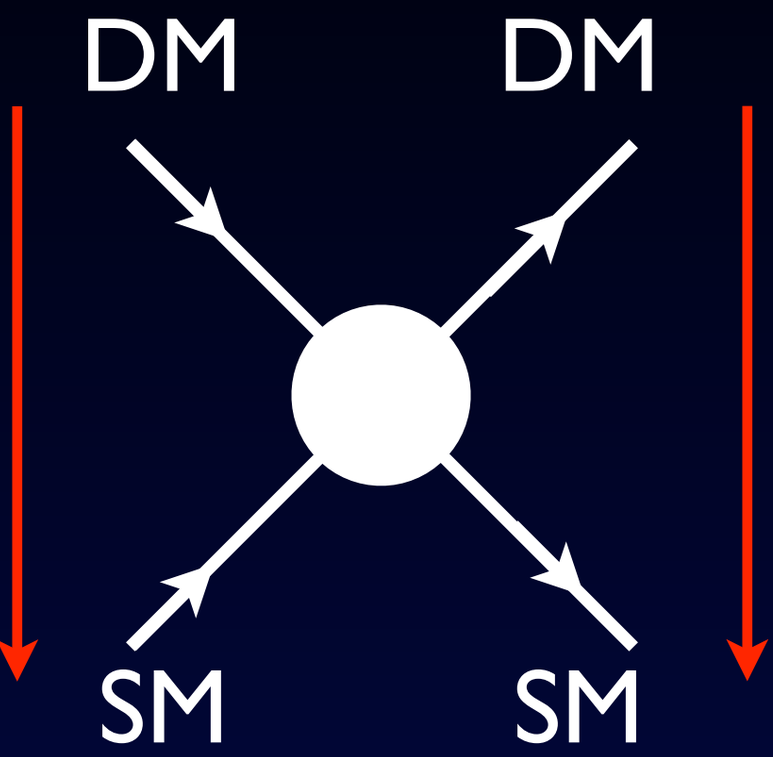
XENON, LUX, PANDA-X, CDMS, Edelweiss, CRESST, PICASSO, COUPP,...

- WIMP hypothesis gets squeezed from all sides
- typically one needs to break the link to the thermal freeze-out cross section somehow

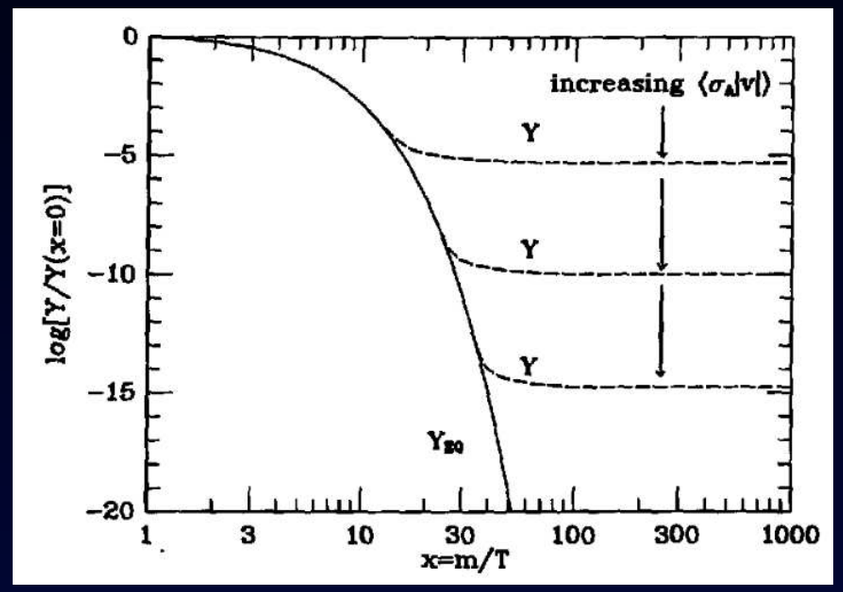
Indirect detection of DM

today





@ freeze-out



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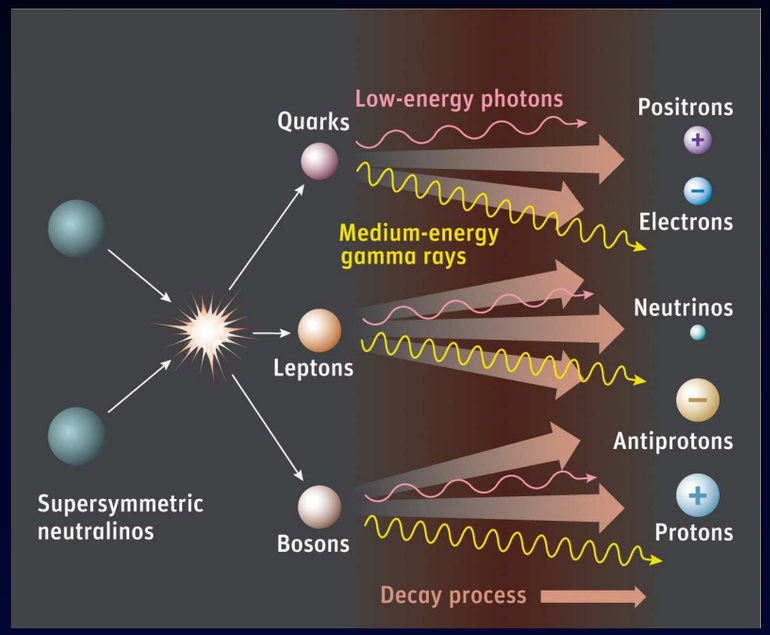

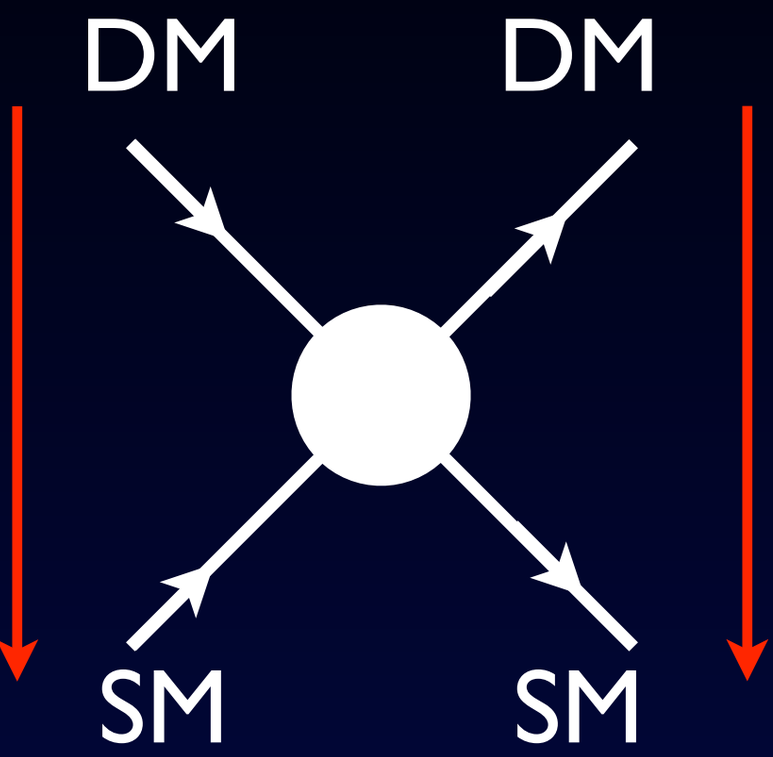

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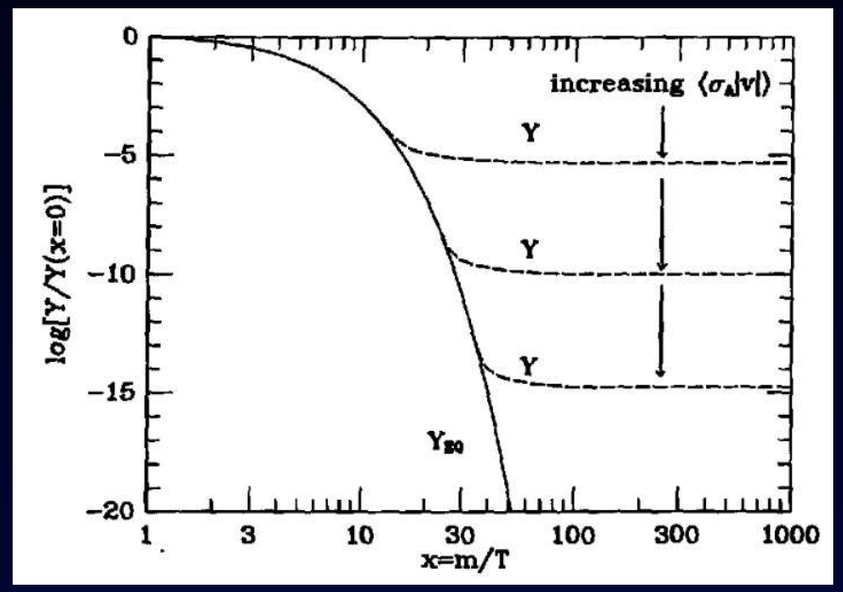
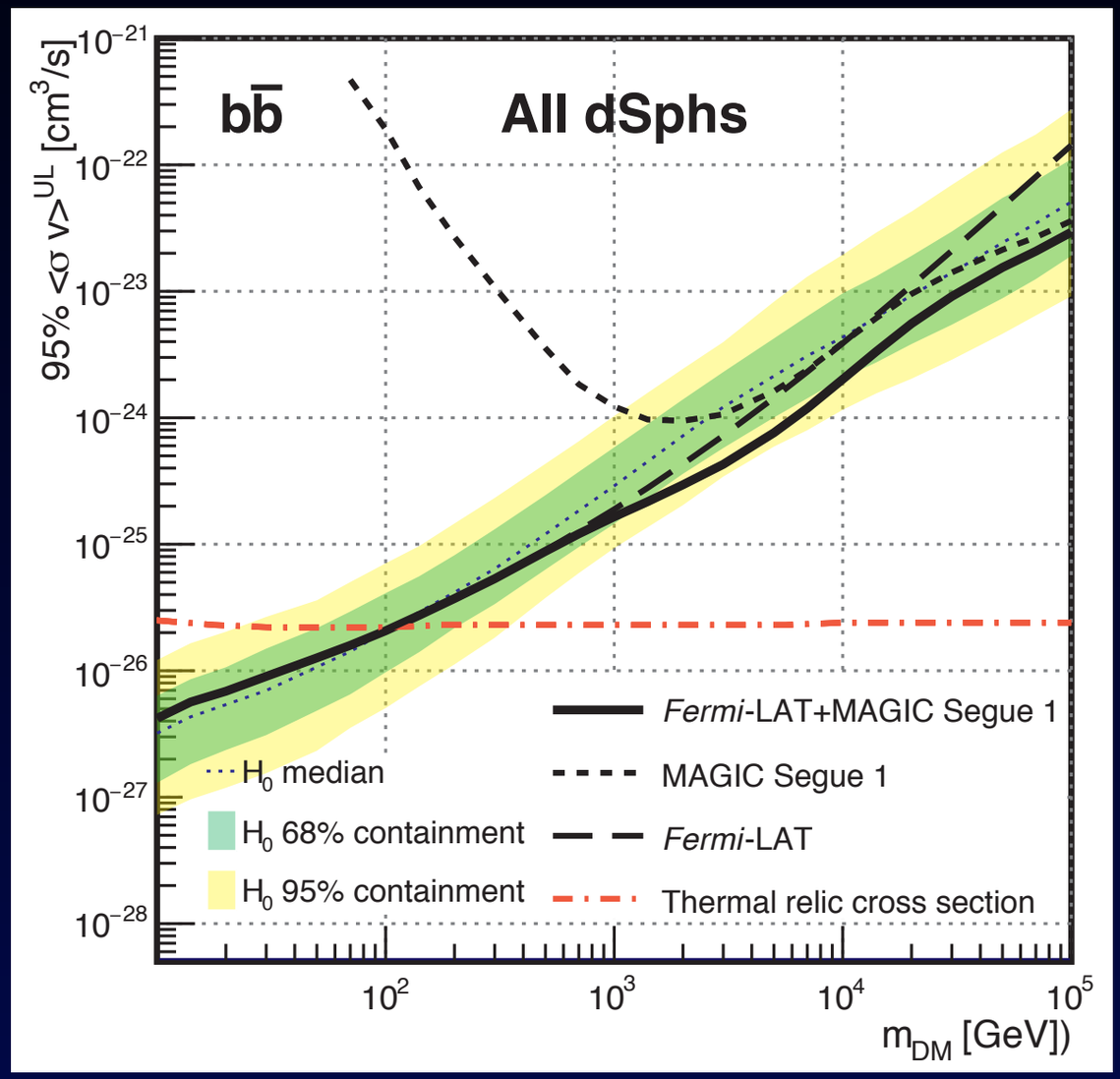


- annihilation cross section today corresponds to the "thermal" one only for s-wave processes (v-independent)
- p-wave annihilations: $\sigma v \sim v^2 \Rightarrow$

  @ freeze-out: $v^2 \sim T/m \sim 0.05\ c^2$
  today: $v \sim 10^{-3}\ c$

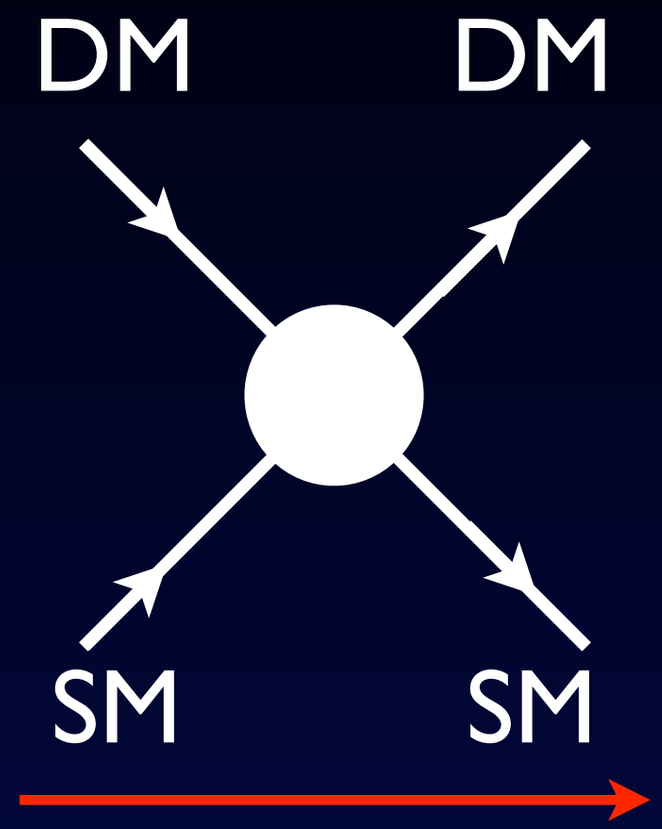
FERMI dwarf spheroidals

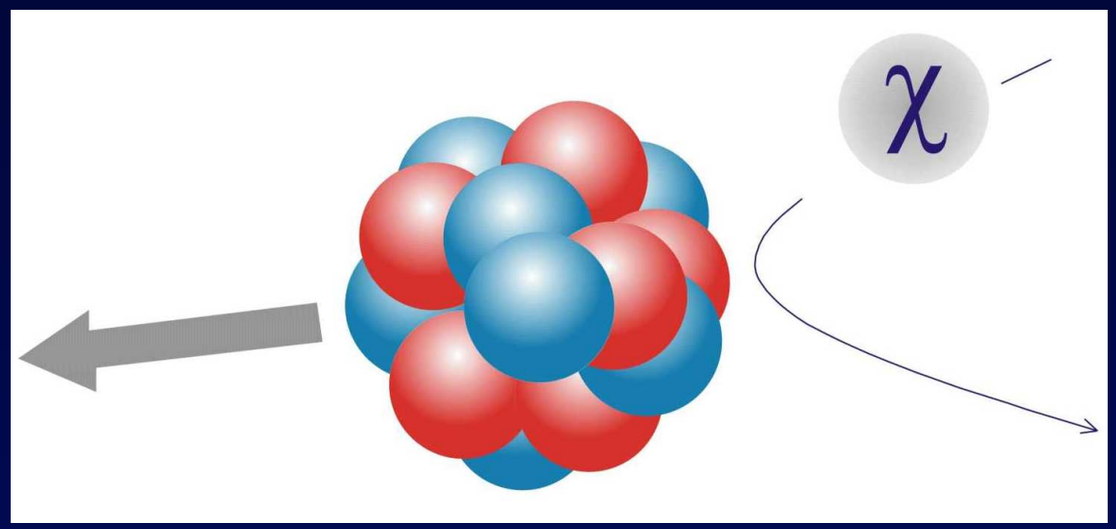
FERMI & MAGIC, 1601.06590



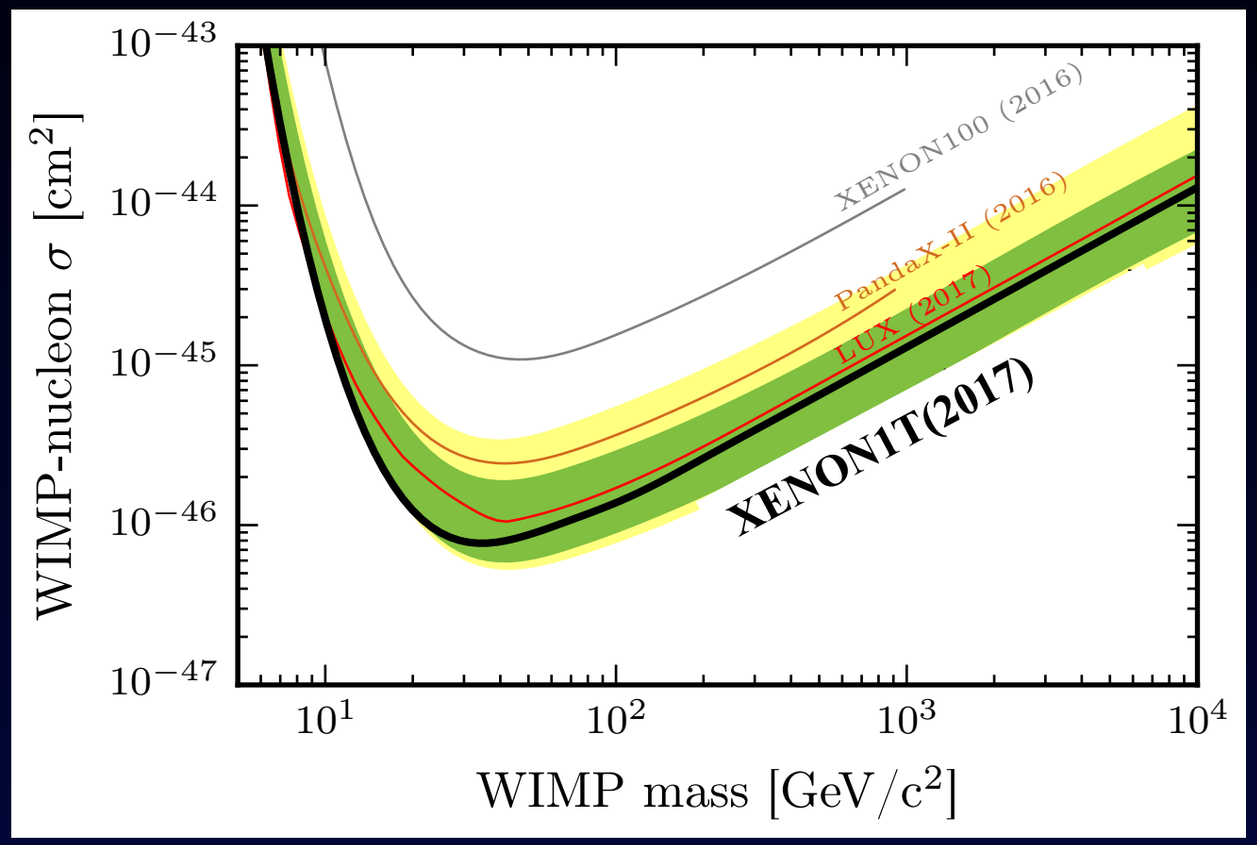
"thermal Xsec" excluded for DM mass < 100 GeV
(assuming s-wave annihilation!)

DM direct detection





Direct detection and the WIMP hypothesis



- testing cross sections ~ 10^{-46} cm^2
- parameter region motivated by WIMP argument (thermal freeze-out) model dependent!

$\sigma_{scatt} < 10^{-46}$ cm^2 $\overset{?}{\leftrightarrow}$ $\sigma_{annih.} \sim 10^{-36}$ cm^2

Direct detection and the WIMP hypothesis

Ex.: Higgs-portal with fermionic DM χ

$$\frac{1}{\Lambda_1}(\overline{\chi}\chi)(H^\dagger H)$$

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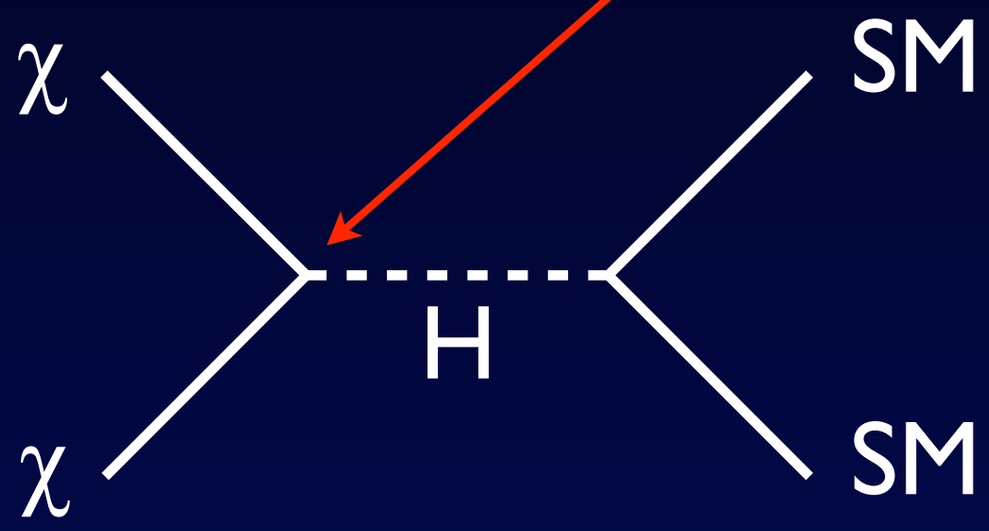
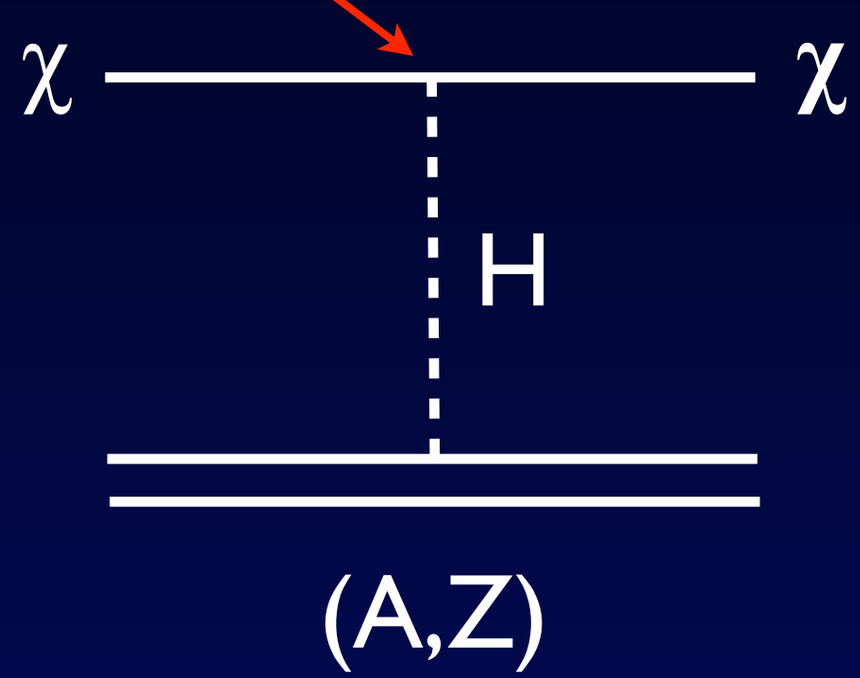
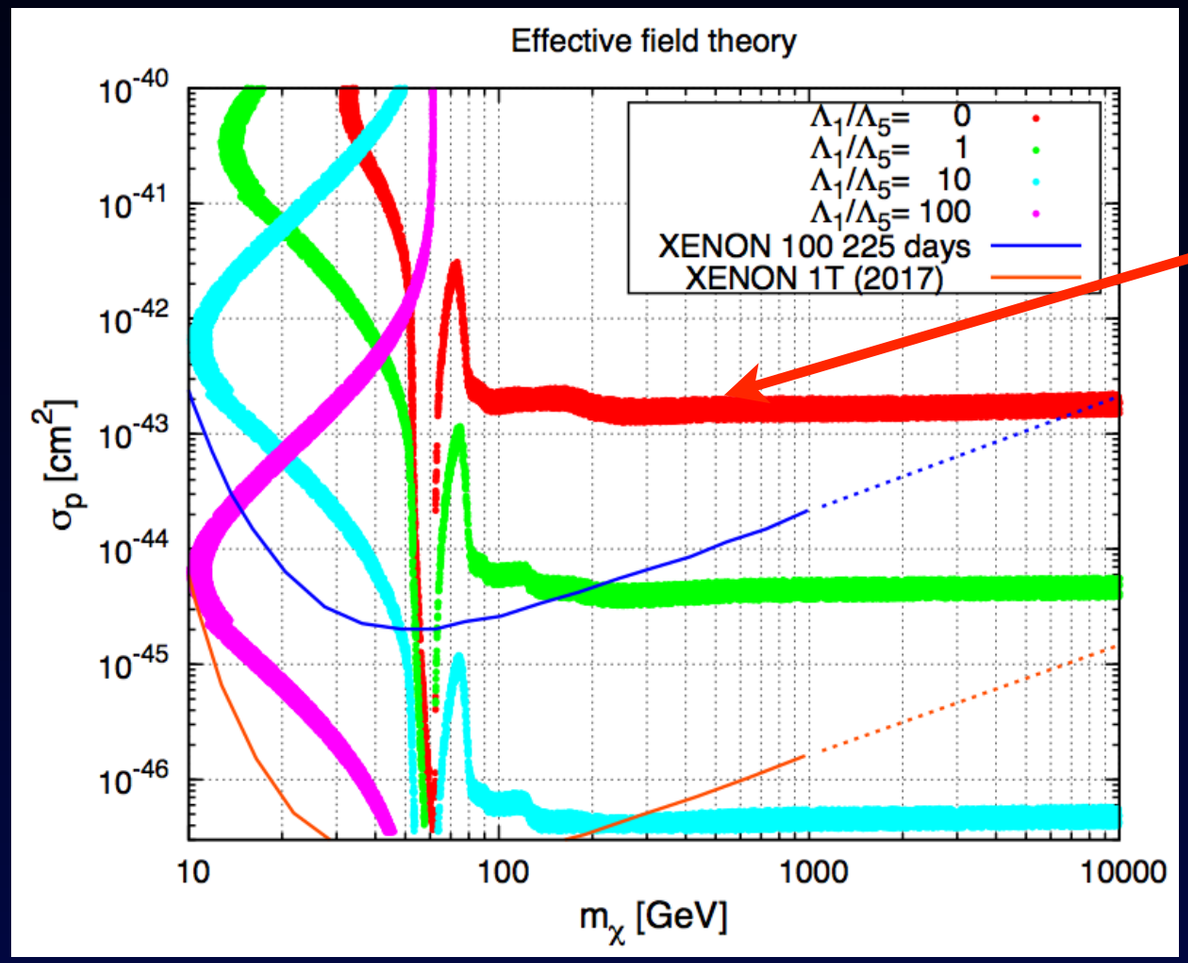
annihilation:



scattering:



Higgs portal



- excluded by XENON, LUX

$$\frac{1}{\Lambda_1}(\overline{\chi}\chi)(H^\dagger H)$$

Lopez-Honorez, TS, Zupan, 12

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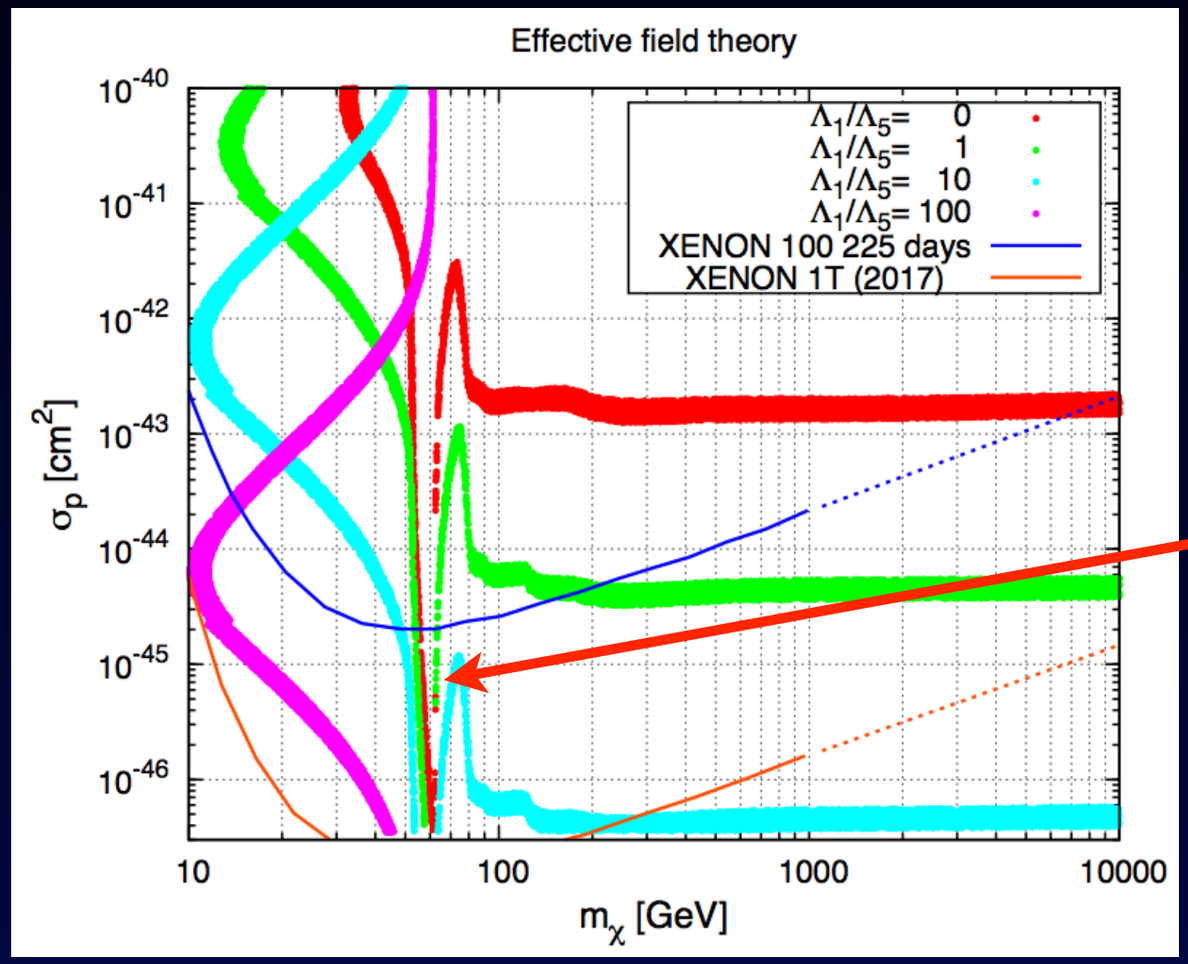

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- s-channel resonance at $m_\chi \approx m_H/2$

Lopez-Honorez, TS, Zupan, 12

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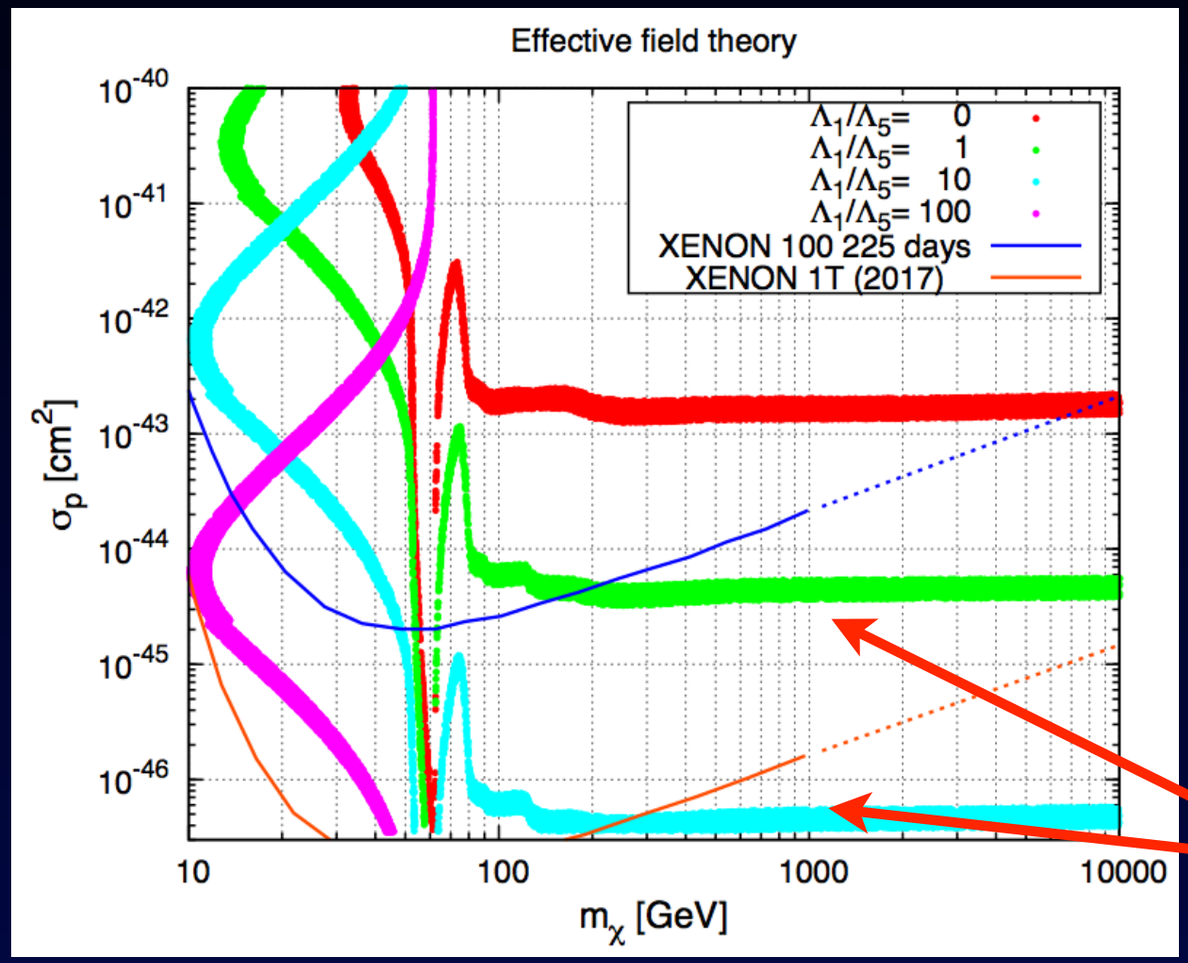


Lopez-Honorez, TS, Zupan, 12

- excluded by XENON, LUX

$$\frac{1}{\Lambda_1}(\overline{\chi}\chi)(H^\dagger H)$$

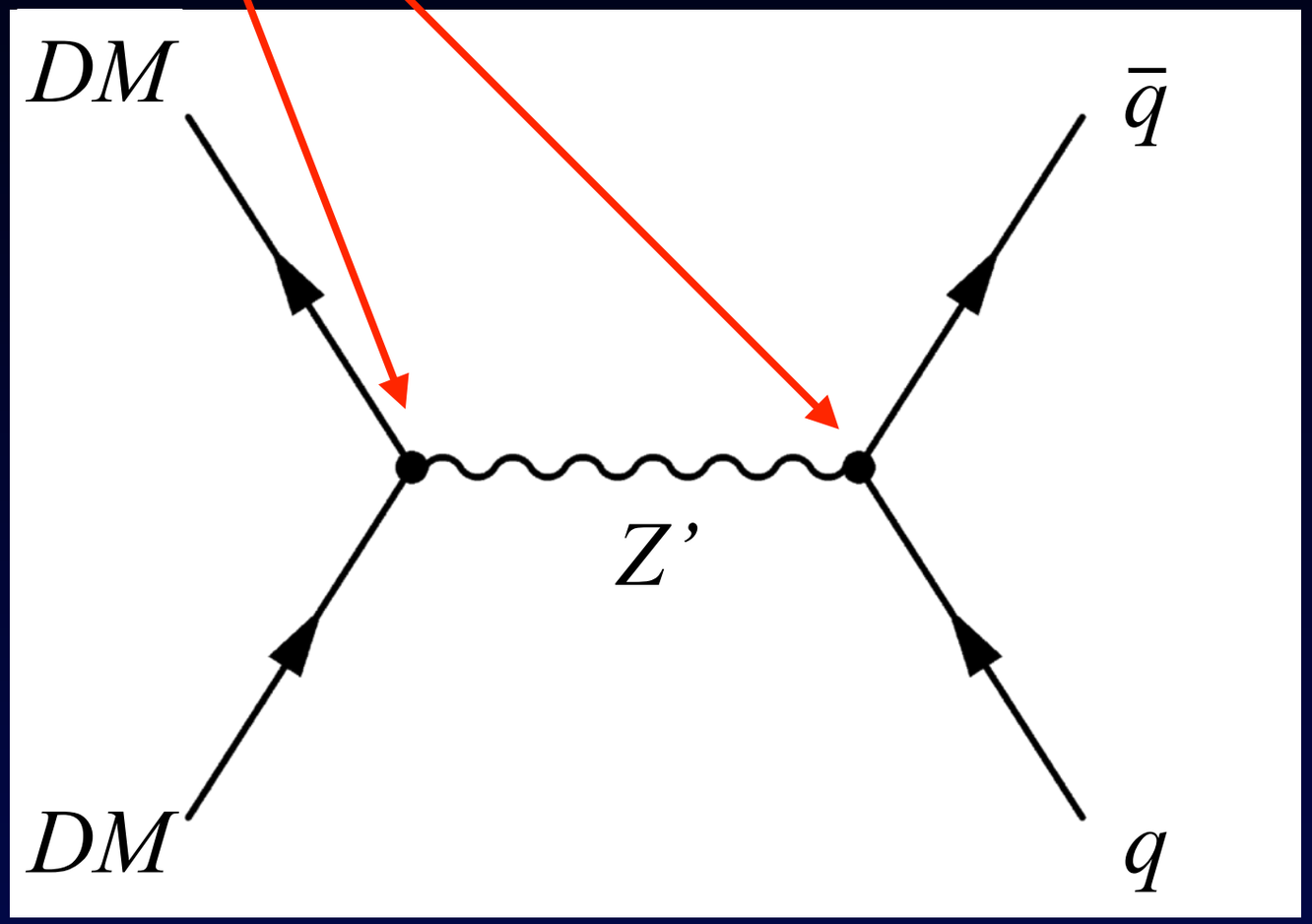
- s-channel resonance at $m_\chi \approx m_H/2$

- pseudo-scalar Higgs-Portal

$$\frac{1}{\Lambda_5}(\overline{\chi}\gamma_5\chi)(H^\dagger H)$$

Example for LHC constraints

Dirac DM, axial-vector couplings to quarks (not leptons)



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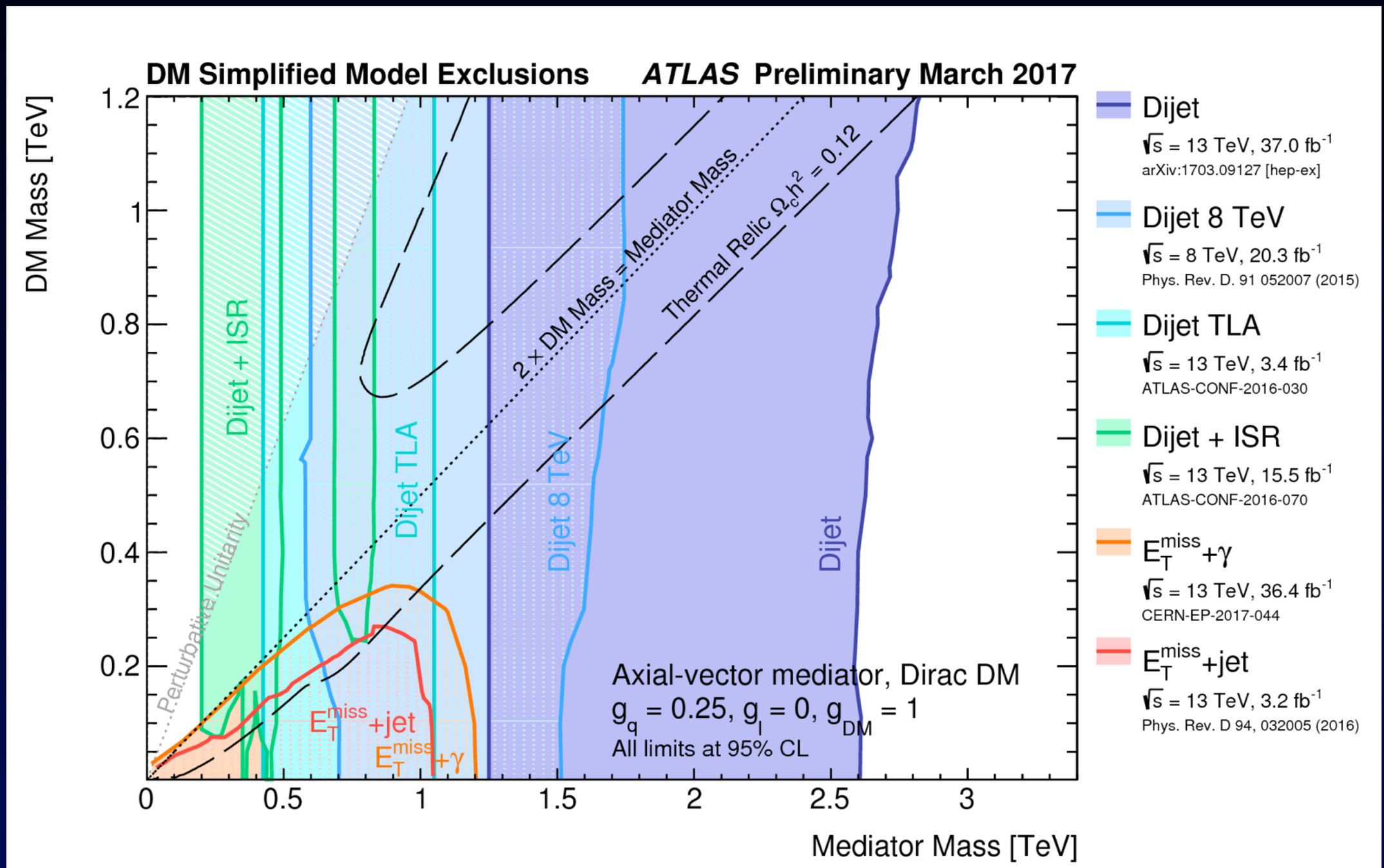


Can we make generic statements about the WIMP hypothesis?

High Energy Physics - Phenomenology

The Waning of the WIMP? A Review of Models, Searches, and Constraints

Giorgio Arcadi, Maíra Dutra, Pradipta Ghosh, Manfred Lindner, Yann Mambrini, Mathias Pierre, Stefano Profumo, Farinaldo S. Queiroz

(Submitted on 21 Mar 2017)

High Energy Physics - Phenomenology

The last refuge of mixed wino-Higgsino dark matter

Martin Beneke, Aoife Bharucha, Andrzej Hryczuk, Stefan Recksiegel, Pedro Ruiz-Femenia

(Submitted on 2 Nov 2016)

High Energy Physics - Phenomenology

Toward (Finally!) Ruling Out Z and Higgs Mediated Dark Matter Models

Miguel Escudero, Asher Berlin, Dan Hooper, Meng-Xiang Lin

(Submitted on 28 Sep 20

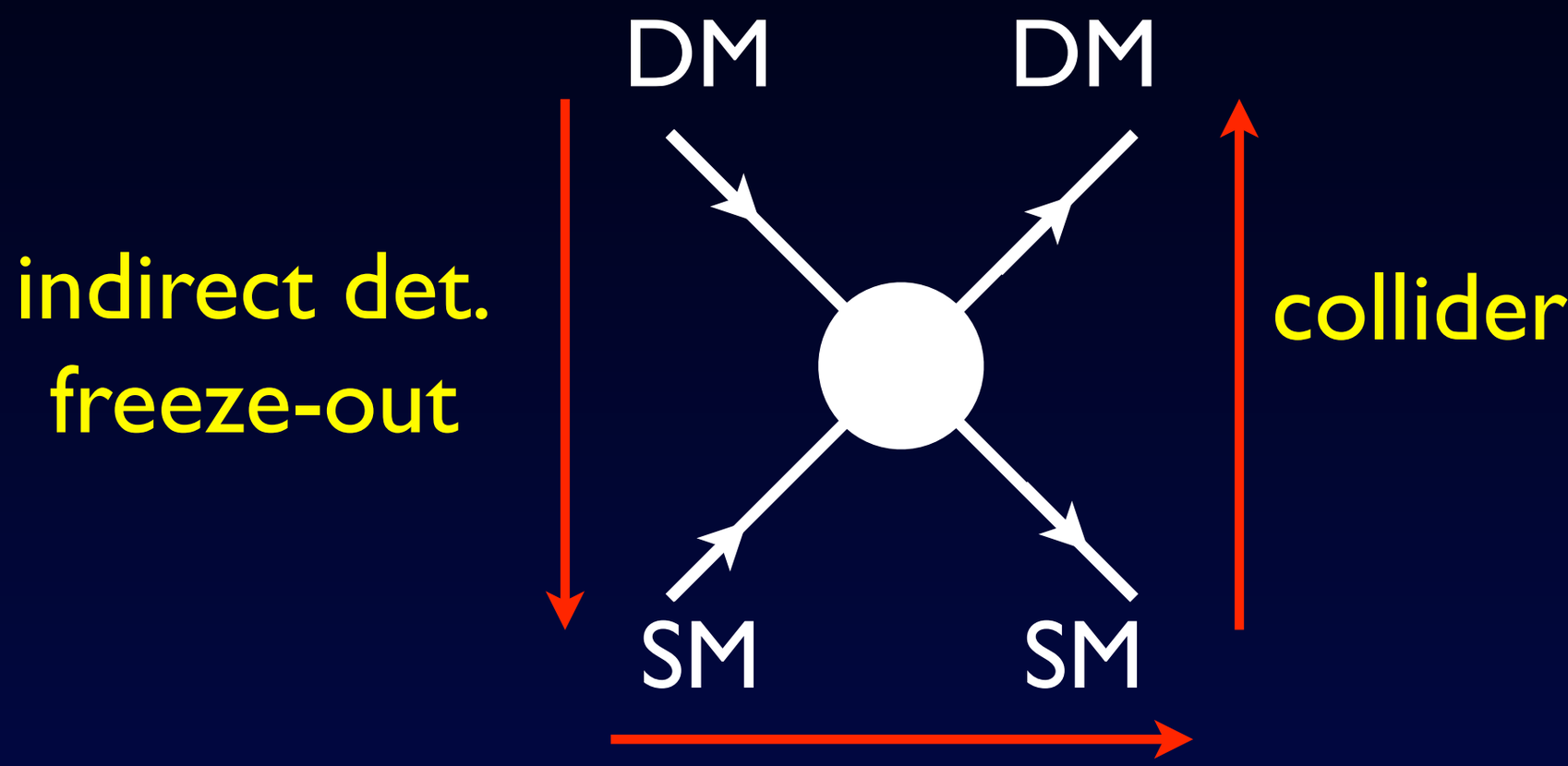
High Energy Physics - Phenomenology

How to save the WIMP: global analysis of a dark matter model with two s-channel mediators

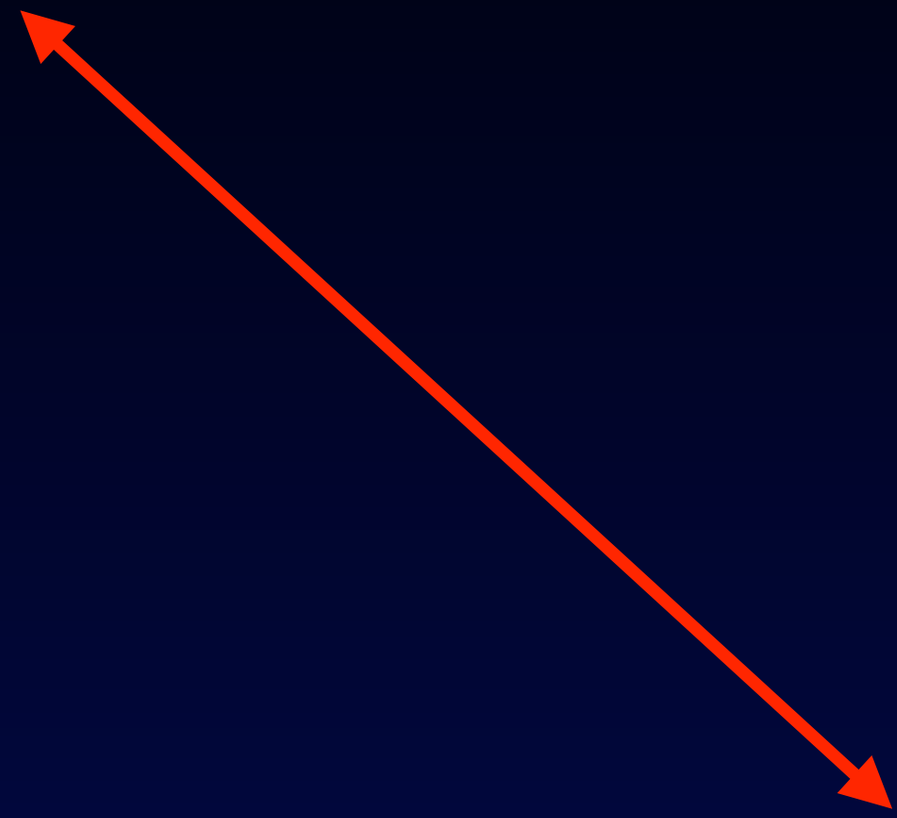
Michael Duerr, Felix Kahlhoefer, Kai Schmidt-Hoberg, Thomas Schwetz, Stefan Vogl

(Submitted on 24 Jun 2016 (v1), last revised 26 Sep 2016 (this version, v2))

The comparison is necessarily model dependent



UV-complete models (SUSY)



"simplified" models
DM particle + mediator(s)

Minimal requirements on a „model“

- SM gauge invariance
- perturbative unitarity

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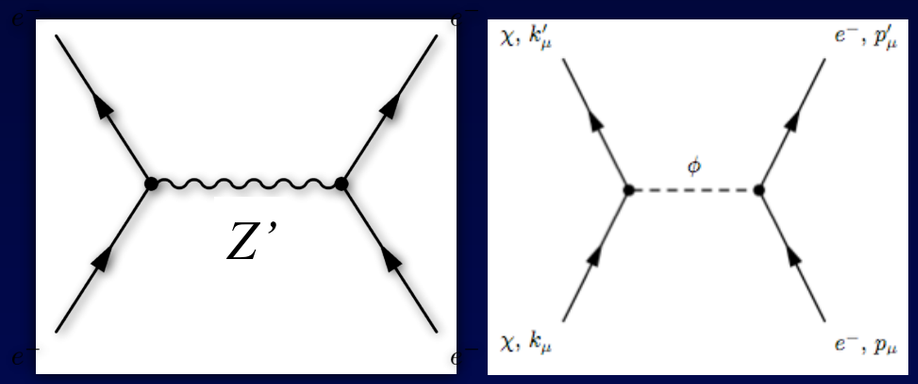
example for „consistent“ model

2-mediator DM (2MDM)



Example for a „consistent simplified“ model

Kahlhöfer, Schmidt-Hoberg, Schwetz, Vogl, 1510.02110
Dürr, Kahlhöfer, Schmidt-Hoberg, Schwetz, Vogl, 1606.07609

SM +

DM fermion + U(1)’ gauge symmetry with Z’ mediator

$$\mathcal{L} = -\sum_{f=q,l,\nu} Z'^{\mu}\, \bar{f}\left[g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5\right] f - Z'^{\mu}\, \bar{\psi}\left[g_{\rm DM}^V \gamma_\mu + g_{\rm DM}^A \gamma_\mu \gamma^5\right] \psi$$

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need „dark Higgs“ S to give mass to Z' and DM

$$\mathcal{L}_S = \left[(\partial^\mu + i\, g_S\, Z'^{\mu}) S\right]^\dagger \left[(\partial_\mu + i\, g_S\, Z'_\mu) S\right] + \mu_s^2\, S^\dagger S - \lambda_s \left(S^\dagger S\right)^2 + y S \bar{\psi}\psi$$

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Higgs mixing and kinetic mixing open new portals to SM

$$+\lambda S^* S H^\dagger H + \chi F'_{\mu\nu} F^{\mu\nu}$$

Z' mediated interaction & gauge invariance

$$\mathcal{L} = -\sum_{f=q,l,\nu} Z'^{\mu}\, \bar{f}\left[g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5\right] f - Z'^{\mu}\, \bar{\psi}\left[g_{\rm DM}^V \gamma_\mu + g_{\rm DM}^A \gamma_\mu \gamma^5\right] \psi$$

$$g_f^V = \frac{1}{2} g'(q_{f_R} + q_{f_L}), \quad g_f^A = \frac{1}{2} g'(q_{f_R} - q_{f_L})$$

gauge invariance of SM Yukawa terms

$$\mathcal{L}_{\rm Yuk} = -\lambda_d \bar{q}_L H q_R - \lambda_u \bar{q}_L \tilde{H} q_R - \lambda_\ell \bar{\ell}_L H \ell_R + h.c.$$

requires:

$$q_H = q_{q_L} - q_{u_R} = q_{d_R} - q_{q_L} = q_{e_R} - q_{\ell_L}$$

(assumes one Higgs doublet)

Z' mediated interaction & gauge invariance

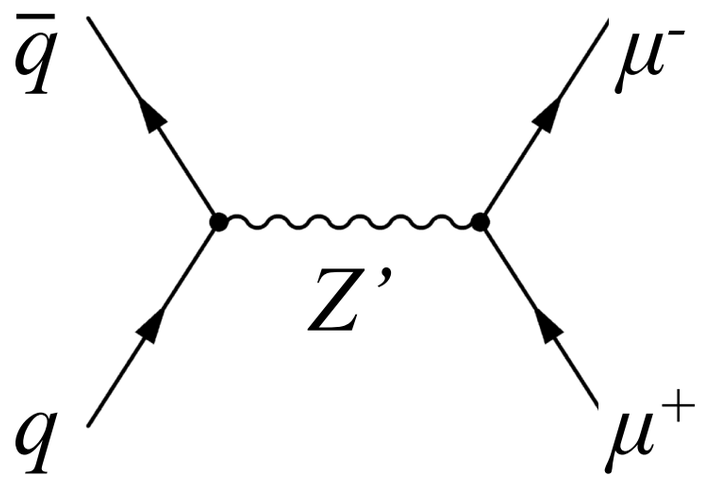
$$\mathcal{L} = -\sum_{f=q,l,\nu} Z'^{\mu}\, \bar{f}\left[g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5\right] f - Z'^{\mu}\, \bar{\psi}\left[g_{\mathrm{DM}}^V \gamma_\mu + g_{\mathrm{DM}}^A \gamma_\mu \gamma^5\right] \psi$$

$$g_f^V = \frac{1}{2} g'(q_{f_R} + q_{f_L}), \quad g_f^A = \frac{1}{2} g'(q_{f_R} - q_{f_L})$$

$$q_H = q_{q_L} - q_{u_R} = q_{d_R} - q_{q_L} = q_{e_R} - q_{\ell_L}$$

for non-zero g^A

- Z' interacts with all generations of quarks and with **leptons**
  $\Rightarrow$ stringent constraints from searches for dilepton resonances



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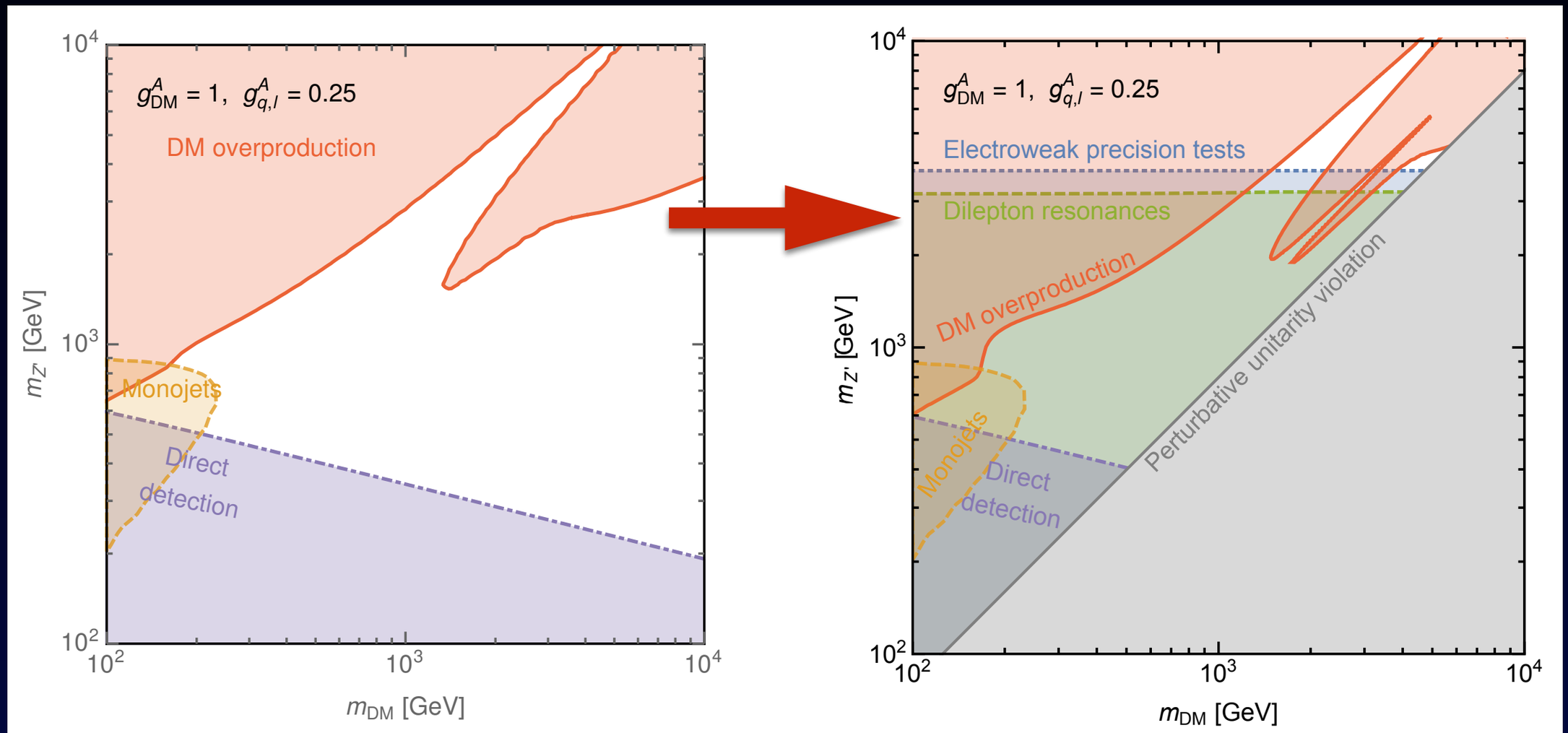
for non-zero g^A

- Z' interacts with all generations of quarks and with **leptons**
  $\Rightarrow$ stringent constraints from searches for dilepton resonances
- off-diagonal mass term $\delta m^2 Z^\mu Z'_\mu$ with

$$\delta m^2 = \frac{1}{2} \frac{e\, g'\, q_H}{s_{\mathrm{W}}\, c_{\mathrm{W}}} v^2$$

$\Rightarrow$ constraints from electroweak precision tests

A-A couplings for `consistent´ model



- stringent constraints from EWPTs and dilepton resonance
- substantial part of parameter space inconsistent
- modified thermal expectation

Example for a „consistent simplified“ model

DM fermion + U(1)' gauge symmetry with Z' mediator

$$\mathcal{L} = -\sum_{f=q,l,\nu} Z'^{\mu}\, \bar{f}\left[g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5\right] f - Z'^{\mu}\, \bar{\psi}\left[g_{\rm DM}^V \gamma_\mu + g_{\rm DM}^A \gamma_\mu \gamma^5\right] \psi$$

need „dark Higgs“ S to give mass to Z' and DM

$$\mathcal{L}_S = \left[(\partial^\mu + i\, g_S\, Z'^{\mu})S\right]^\dagger \left[(\partial_\mu + i\, g_S\, Z'_\mu)S\right] + \mu_s^2\, S^\dagger S - \lambda_s \left(S^\dagger S\right)^2 + y S \bar{\psi}\psi$$

Higgs mixing and kinetic mixing open new portals to SM

$$+\lambda S^* S H^\dagger H + \chi F'_{\mu\nu} F^{\mu\nu}$$

Example for a „consistent simplified“ model

assume no coupl. to leptons and equal couplings to all quarks → U(1)' corresponds to baryon number

DM fermion + U(1)' gauge symmetry with Z' mediator

$$\mathcal{L} = -\sum_{f=q,l,\nu} Z'^{\mu}\, \bar{f}\left[g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5\right] f - Z'^{\mu}\, \bar{\psi}\left[g_{\mathrm{DM}}^V \gamma_\mu + g_{\mathrm{DM}}^A \gamma_\mu \gamma^5\right] \psi$$

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Higgs mixing and kinetic mixing open new portals to SM

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Example for a „consistent simplified“ model

not independent for given masses:
only one dark-sector coupling

DM fermion + U(1)' gauge symmetry with Z' mediator

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Higgs mixing and kinetic mixing open new portals to SM

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Example for a „consistent simplified“ model

assume only loop-induced kinetic mixing

DM fermion + U(1)' gauge symmetry with Z' mediator

$$\mathcal{L} = -\sum_{f=q,l,\nu} Z'^{\mu}\,\bar{f}\left[g_f^V\gamma_\mu + g_f^A\gamma_\mu\gamma^5\right] f - Z'^{\mu}\,\bar{\psi}\left[g_{\rm DM}^V\gamma_\mu + g_{\rm DM}^A\gamma_\mu\gamma^5\right]\psi$$

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$$\mathcal{L}_S = \left[(\partial^\mu + i\,g_S\,Z'^{\mu})S\right]^\dagger\left[(\partial_\mu + i\,g_S\,Z'_\mu)S\right] + \mu_s^2\,S^\dagger S - \lambda_s\left(S^\dagger S\right)^2 + yS\bar{\psi}\psi$$

Higgs mixing and kinetic mixing open new portals to SM

$$+\lambda S^* S H^\dagger H + \chi F'_{\mu\nu}F^{\mu\nu}$$

Example for a „consistent simplified“ model

Comment on anomalies:

- additional states are needed to cancel anomalies
- gauge symmetries & vectorial Z’ coupling imply that there is no color anomaly →
- no colored states needed
  small impact on phenomenology

e.g., Dürr, Fileviez Perez, 1309.3970; Ekstedt et al., 1605.04855; Ellis, Fairbairn, Tunney, 1704.03850

Example for a „consistent simplified“ model

- parameters of the 2MDM model:
  3 masses
  3 couplings
- fix one coupling by relic density

particle masses		coupling constants	
DM mass	m_χ	dark-sector coupling	g_χ or y_χ
Z' mass	$m_{Z'}$	quark–Z' coupling	g_q
dark Higgs mass	m_s	Higgs mixing angle	θ

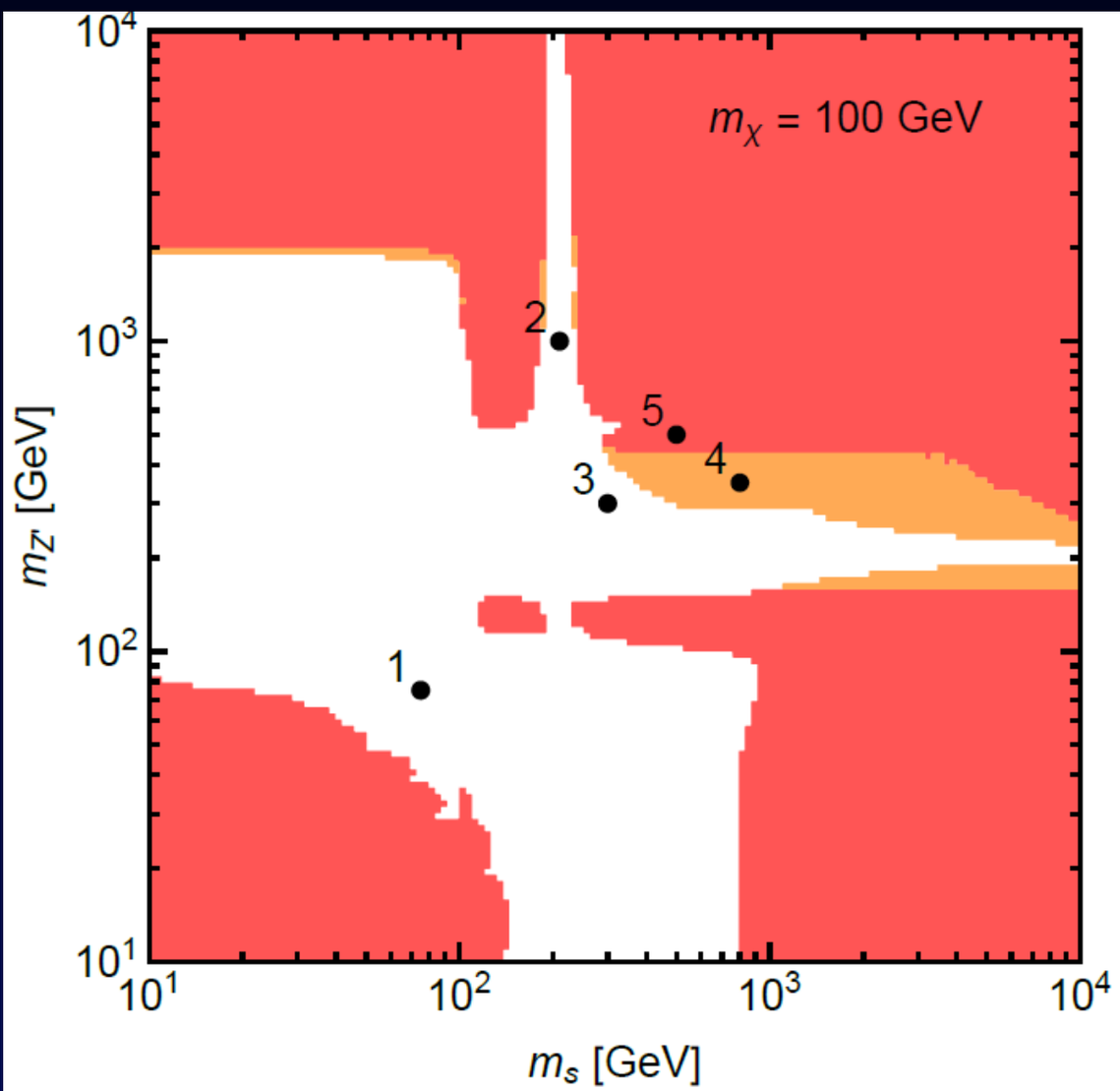
Example for a „consistent simplified“ model

- parameters of the 2MDM model:
  3 masses
  3 couplings
- fix one coupling by relic density
- impose constraints from:
  - direct and indirect DM searches
  - monojets, dijets, dileptons at colliders
  - Higgs observables
  - electroweak precision tests
  - perturbative unitarity

Dürr, Kahlhöfer, Schmidt-Hoberg, TS, Vogl, 1606.07609

global parameter scan

Dürr, Kahlhöfer, Schmidt-Hoberg, TS, Vogl, 1606.07609



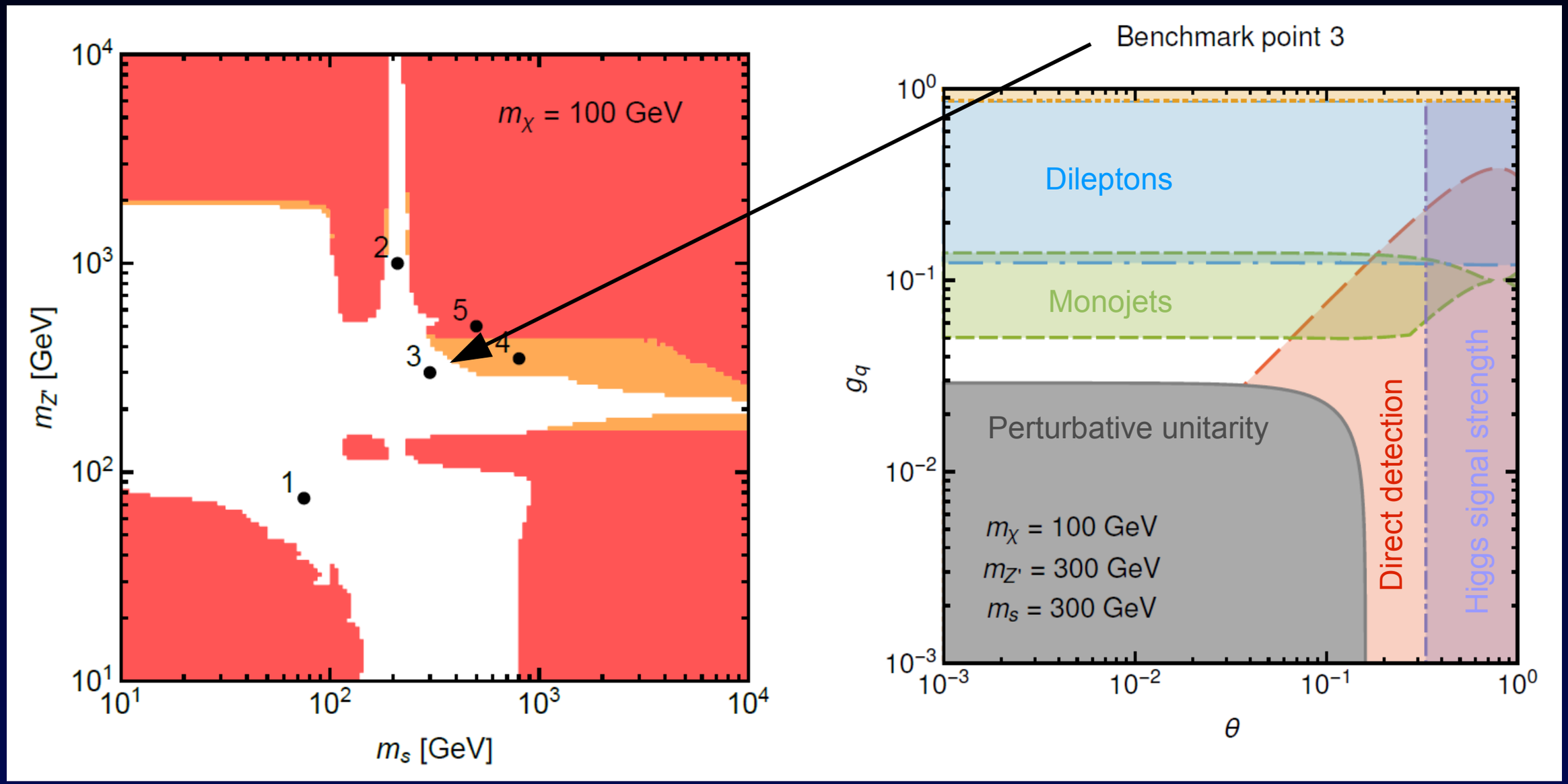
Red: All coupling combinations are excluded by at least one constraint.

White: At least one coupling combination is compatible with all constraints.

Orange: Large values of g_q cannot reliably be excluded due to the mediator width becoming large ($\Gamma/m_{Z'} > 0.3$).

global parameter scan

WIMP hypothesis survives only in special corners:



global parameter scan

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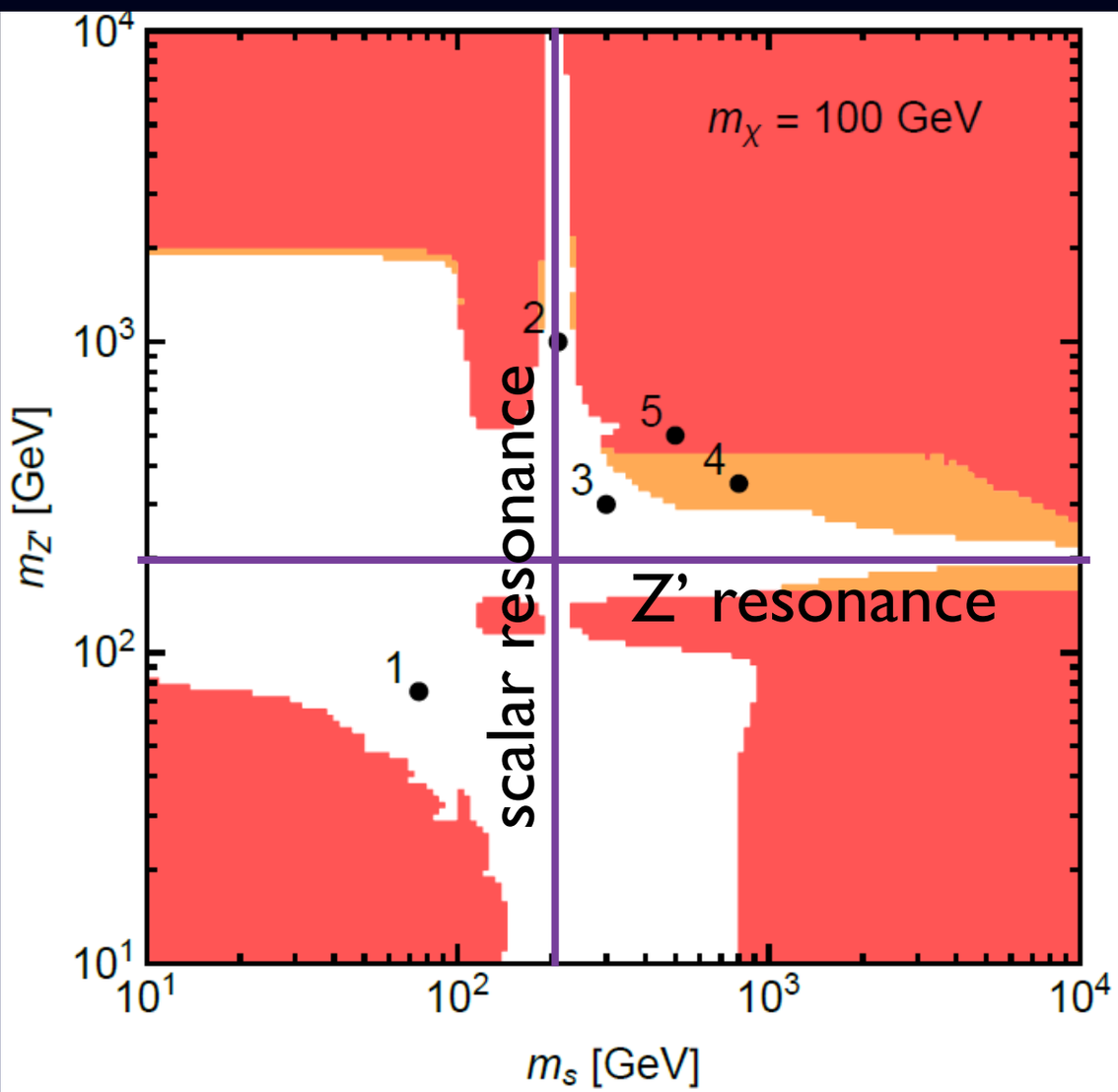
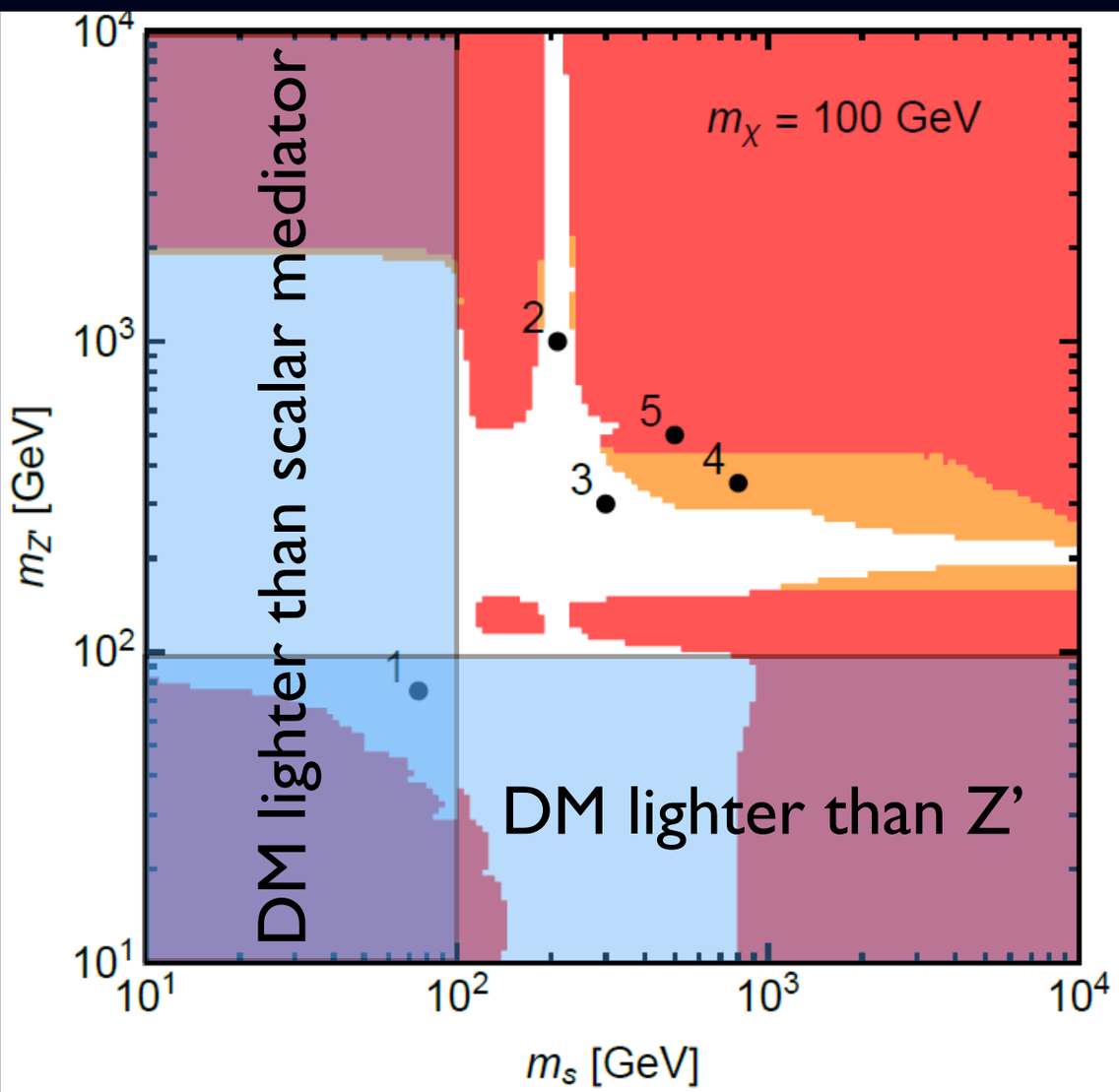


- close to an s-channel resonance:

$\chi\chi \rightarrow$ s/Z' $\rightarrow$ SM SM

global parameter scan

WIMP hypothesis survives only in special corners:



- close to an s-channel resonance:

  $\chi\chi \rightarrow$ s/Z' $\rightarrow$ SM SM

- one or both mediators are lighter than DM → „terminator“ or „secluded DM“

Saving the WIMP by a light mediator: Secluded DM *Pospelov, Ritz, Voloshin, 2007*

$$\mathcal{L} = -\sum_{f=q,l,\nu} Z'^{\mu}\, \bar{f}\left[g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5\right] f - Z'^{\mu}\, \bar{\psi}\left[g_{\rm DM}^V \gamma_\mu + g_{\rm DM}^A \gamma_\mu \gamma^5\right] \psi$$

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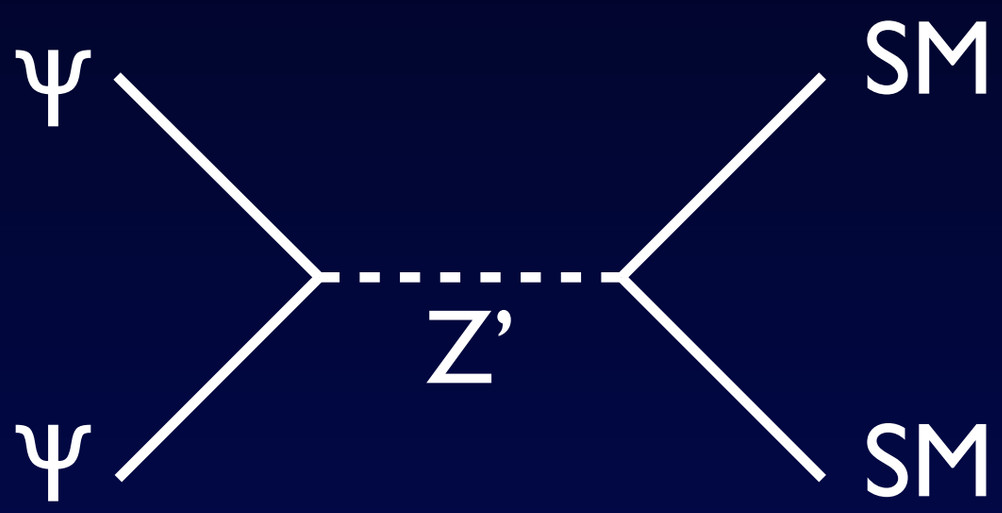

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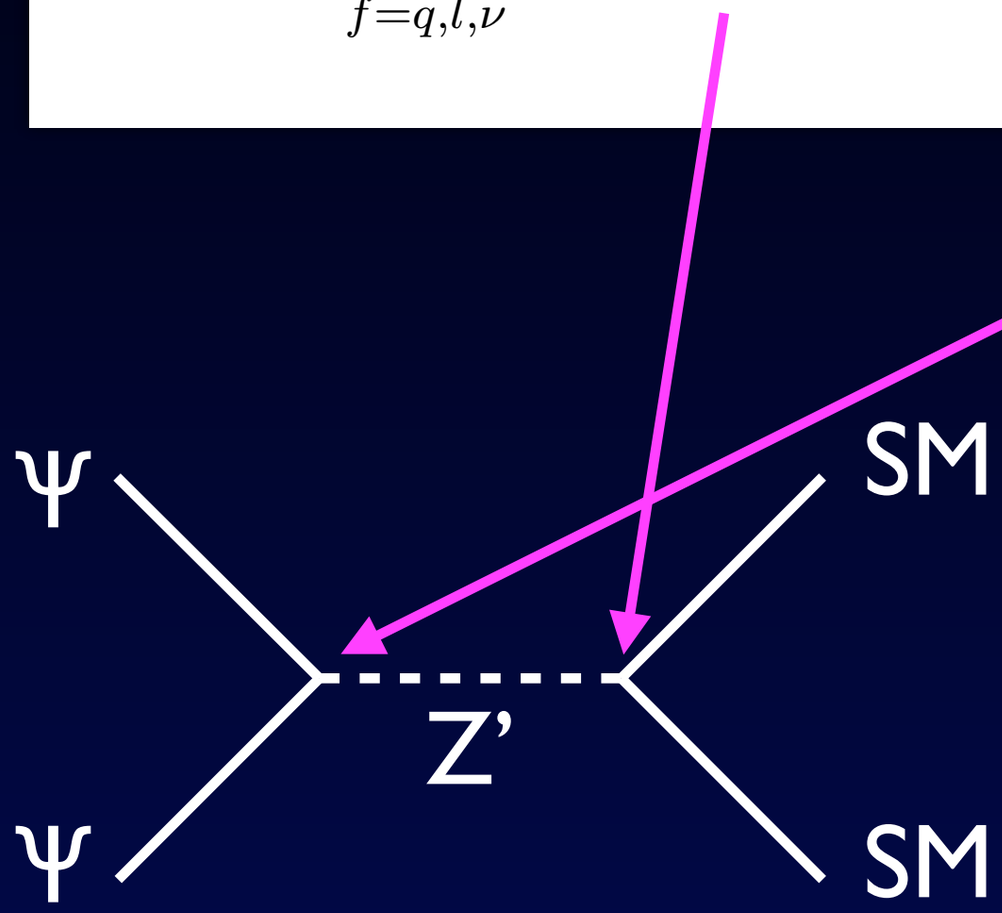

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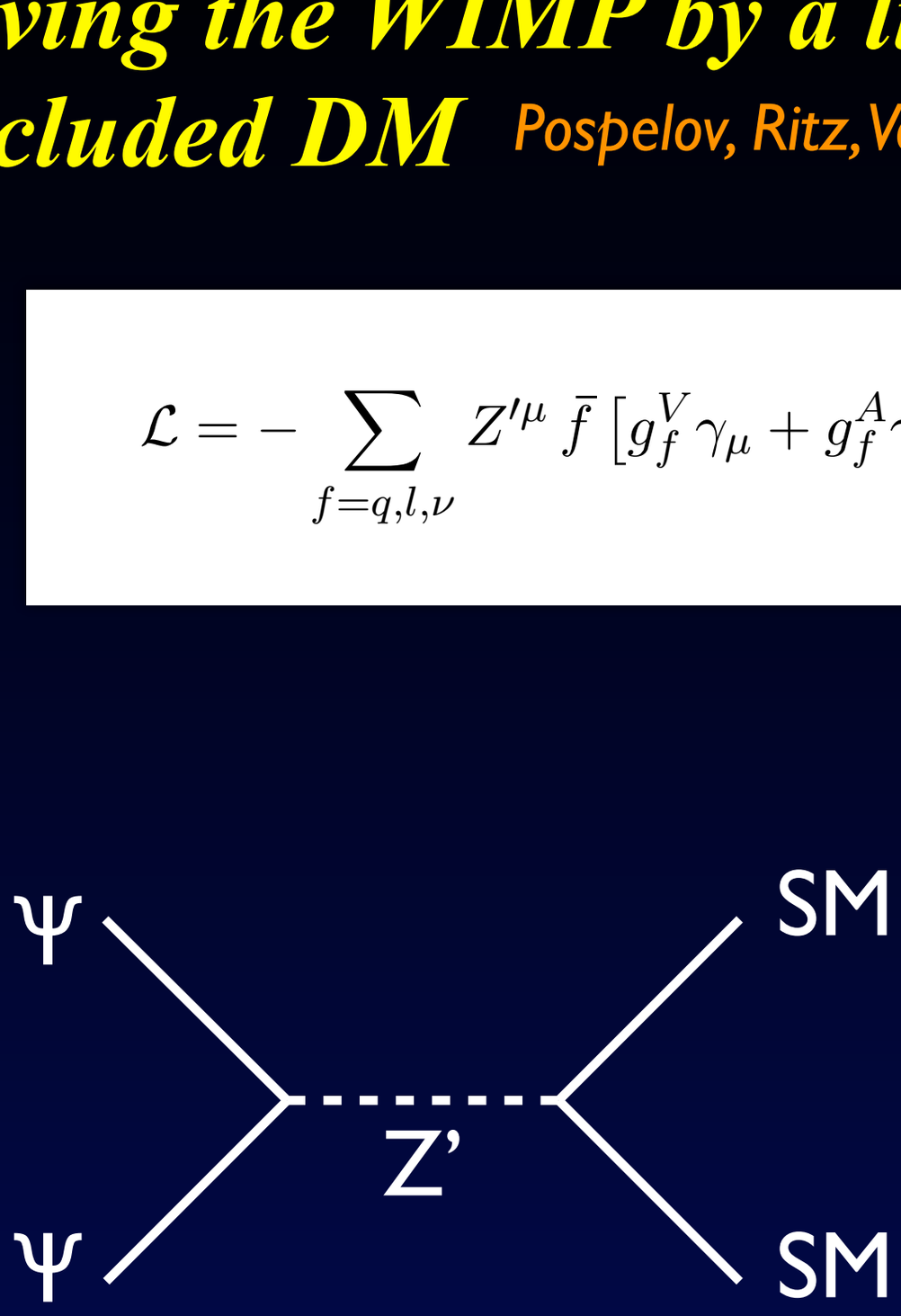
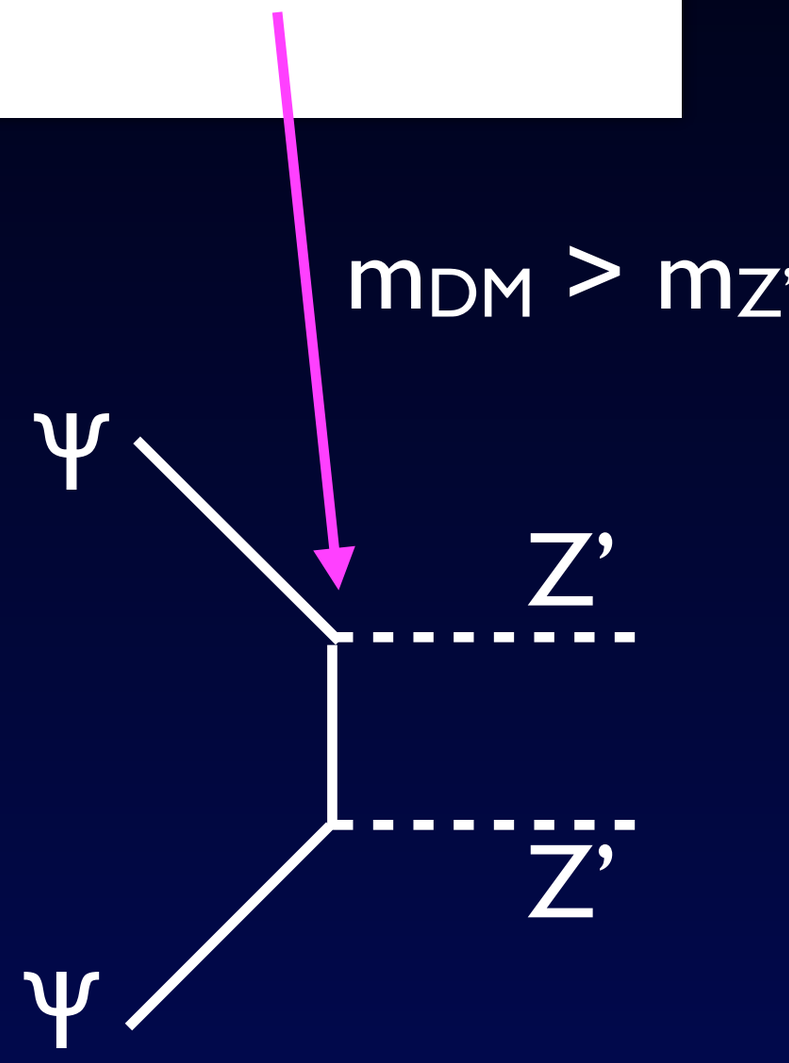
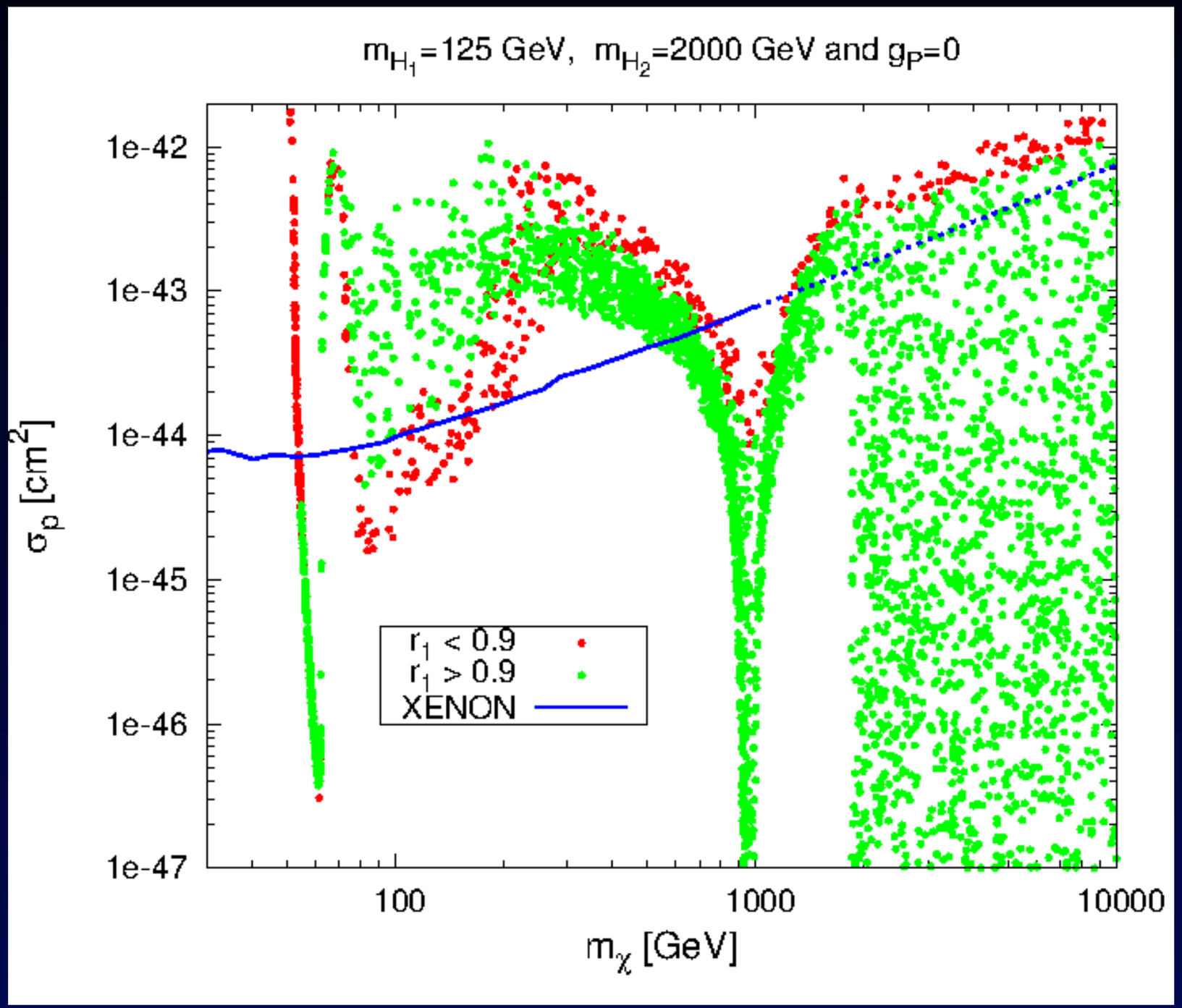




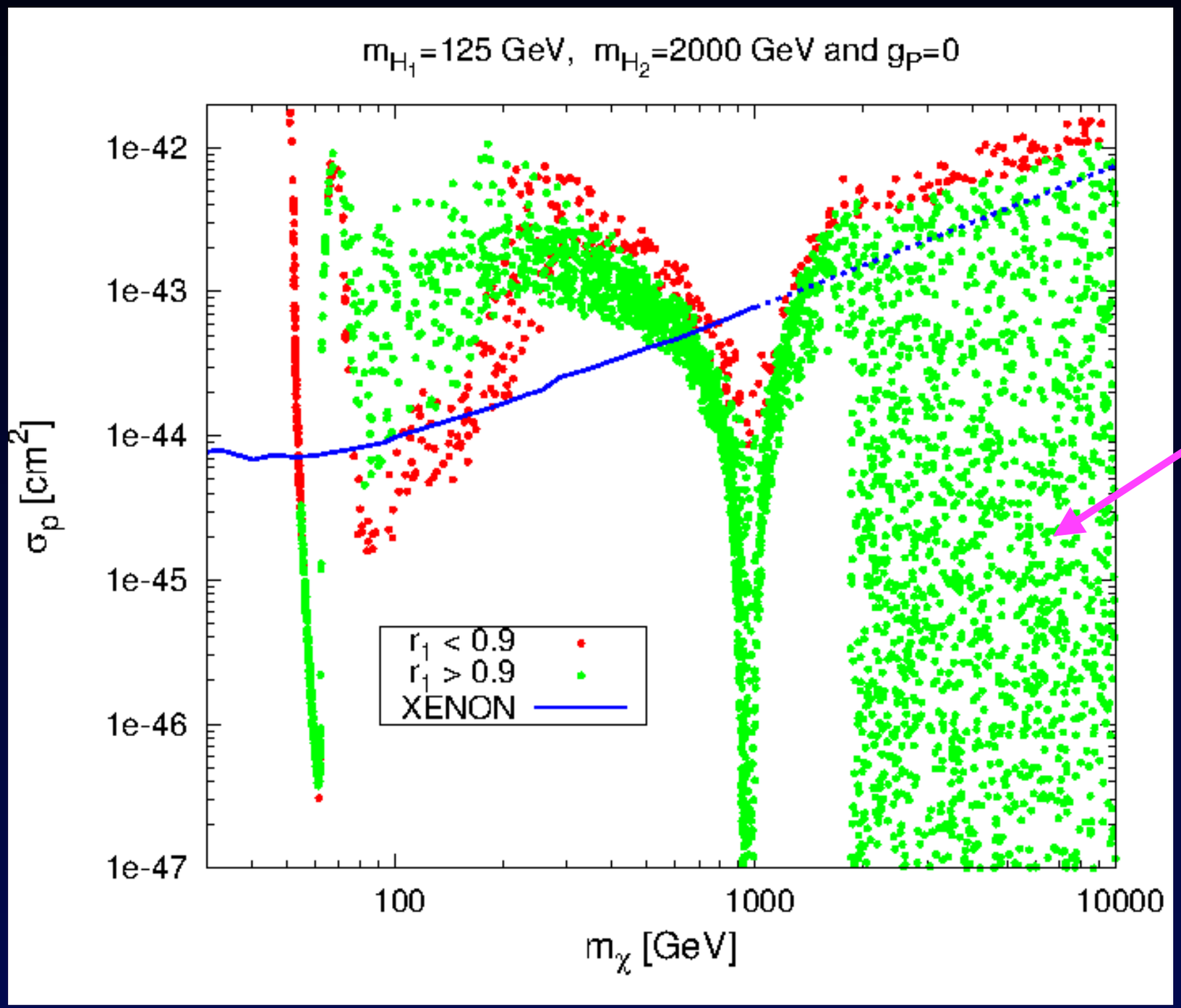
Secluded DM - scalar terminator



example with scalar mediator

Lopez-Honorez, TS, Zupan, 12

Secluded DM - scalar terminator

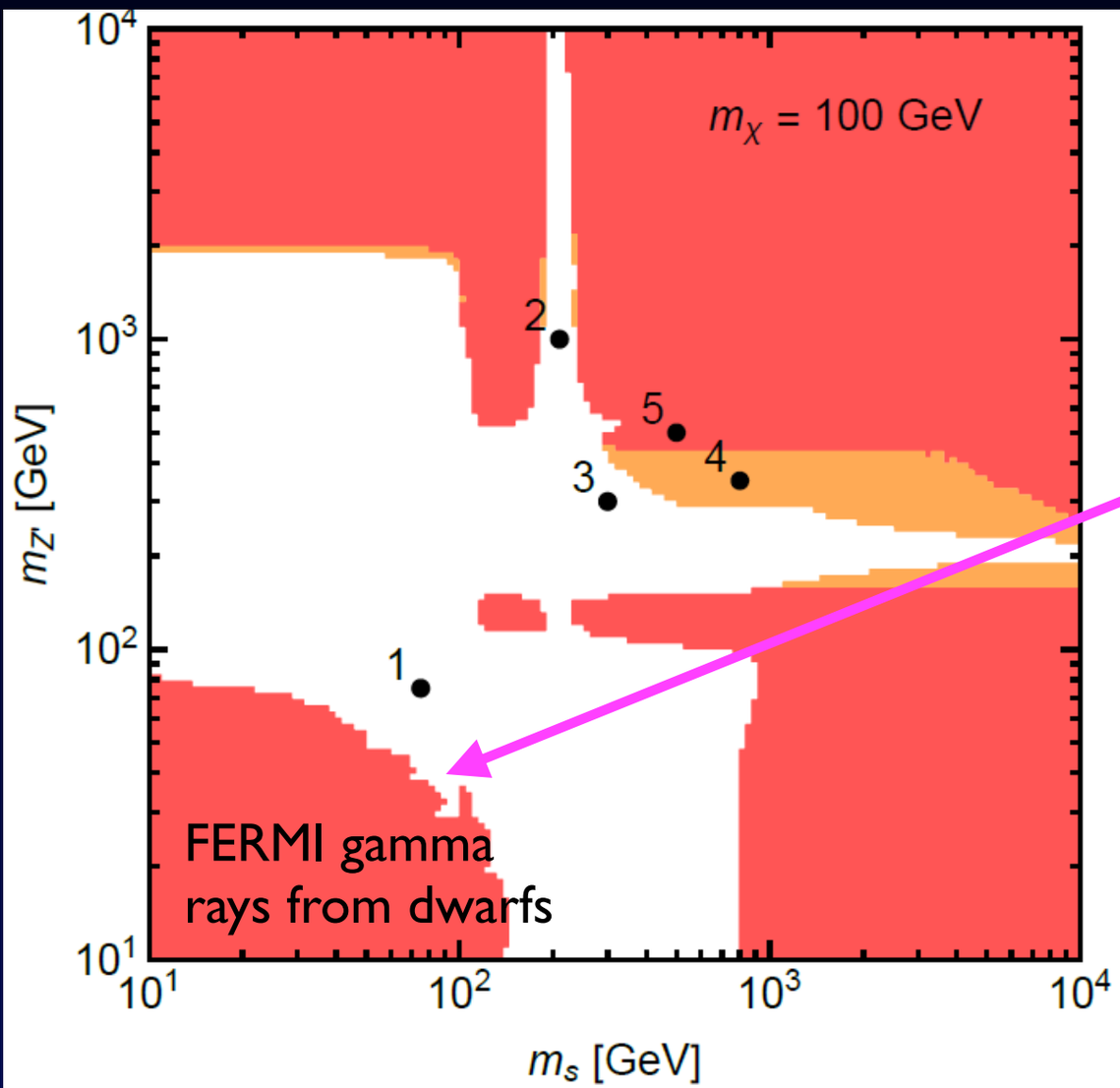


example with scalar mediator

dark terminator

Lopez-Honorez, TS, Zupan, 12

A potential signal from light mediators



- in some cases there is hope for signals in indirect detection (s-channel annihilation)

Remarks - 1

- thermally produced DM („WIMP“) links DM to weak-scale physics
- cornered from direct, indirect, and collider searches
- comparison necessarily model dependent

Remarks - 2

- request some minimal consistency properties (SM gauge invariance, perturb. unitarity,…)

- considered 2-mediator DM (2MDM)
  Majorana DM SM-singlet, U(1)' symmetry
  s-channel vector and scalar mediator
  gauge invariant, UV-complete (up to anomaly)

- confined to special corners:
  either to s-channel resonance or to a „dark terminator“ ($m_{med} < m_{DM}$)

Remarks - 3

- qualitative similar conclusions should hold for a wide class of WIMP models

ex. alternative scenarios:

- DM (partially) gauged under SM
  (e.g., minimal DM, well-tempered DM)

  Cirelli, Fornengo, Strumi, 05;
  Arkani-Hamed, Delgado, Giudice, 06;
  Banerjee, Matsumoto, Mukaida, Tsai, 16

- co-annihilations *Baker et al., 1510.03434*
  t-channel mediator: $y\ q_R\ X\ \eta$ *Garny, Ibarra, Rydbeck, Vogl, 14*

Conclusions

We have cornered the WIMP.

The time has come
to discover it!

Conclusions

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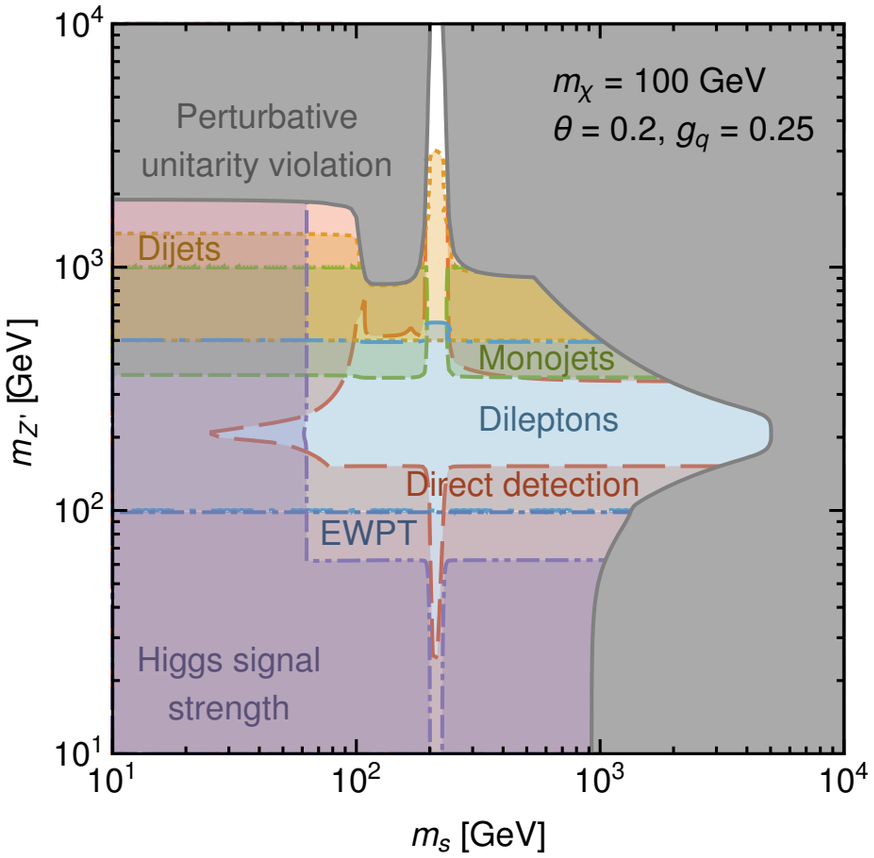
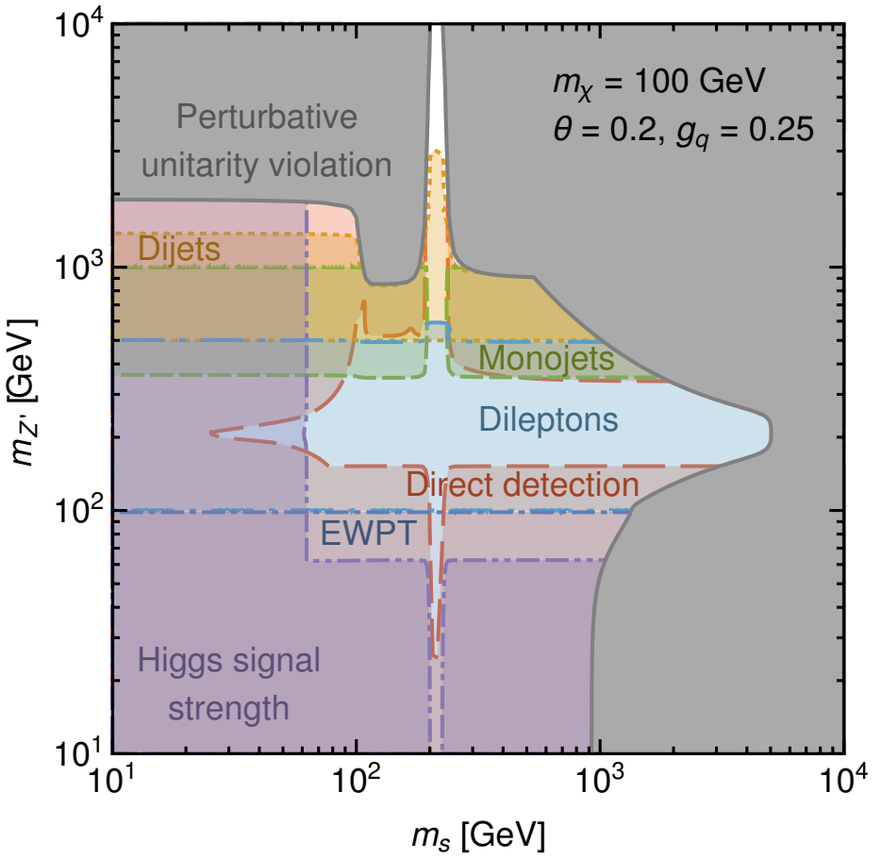
The time has come
to discover it!

Thank you!


m_χ = 100 GeV
θ = 0.2, g_q = 0.25
Perturbative unitarity violation
Dijets
Monojets
Dileptons
Direct detection
EWPT
Higgs signal strength
$m_{Z'}$ [GeV]
m_s [GeV]
10^1
10^2
10^3
10^4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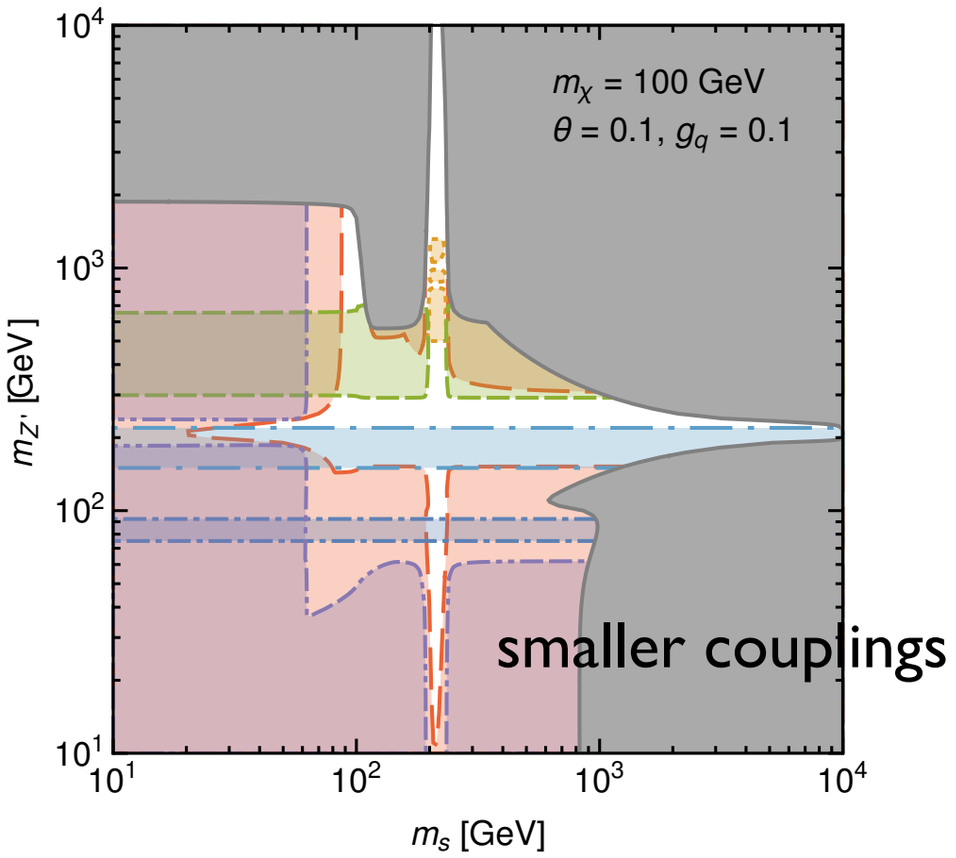
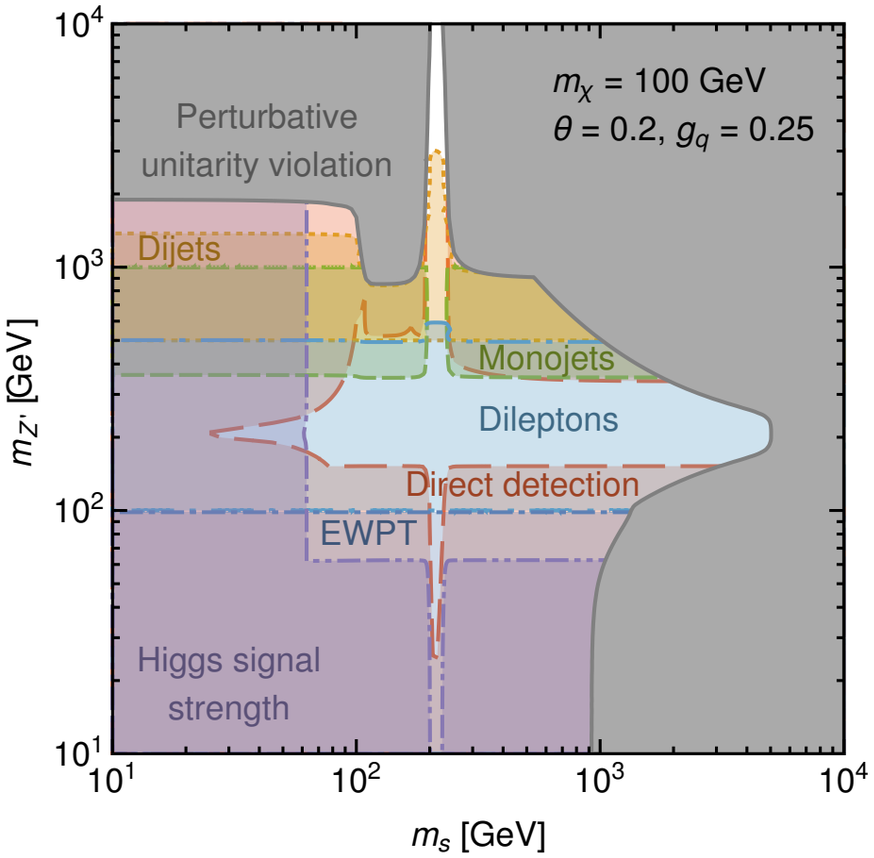

m_χ = 100 GeV
θ = 0.1, g_q = 0.1
smaller couplings
$m_{Z'}$ [GeV]
m_s [GeV]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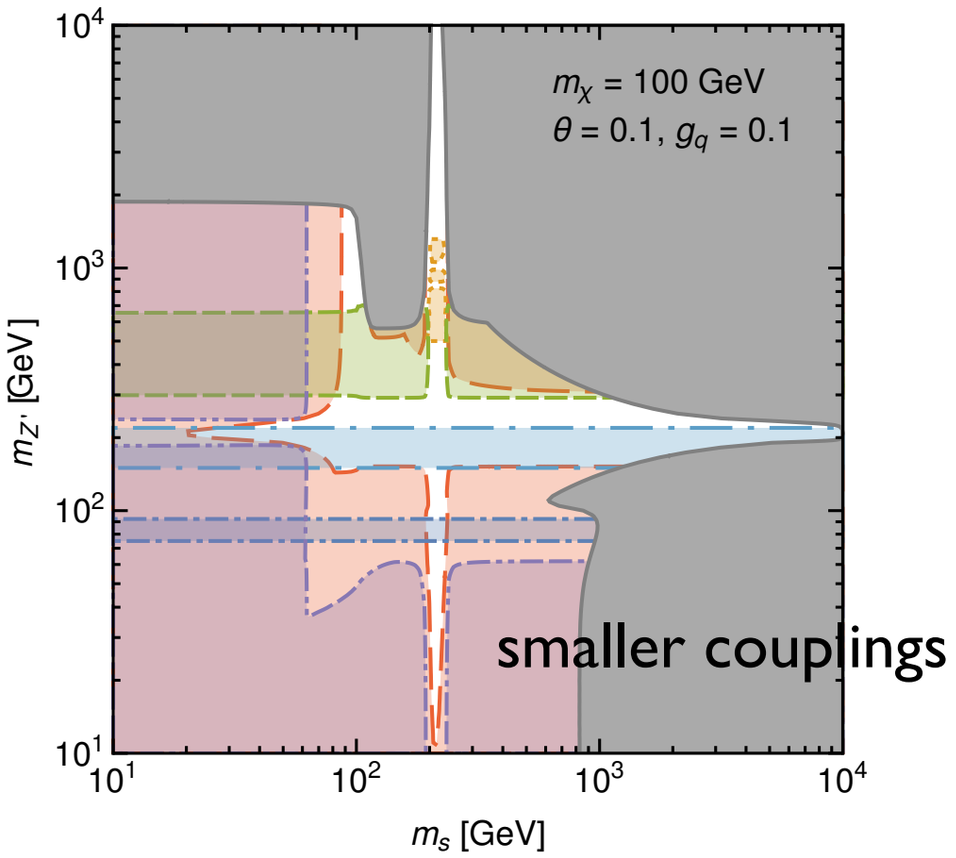
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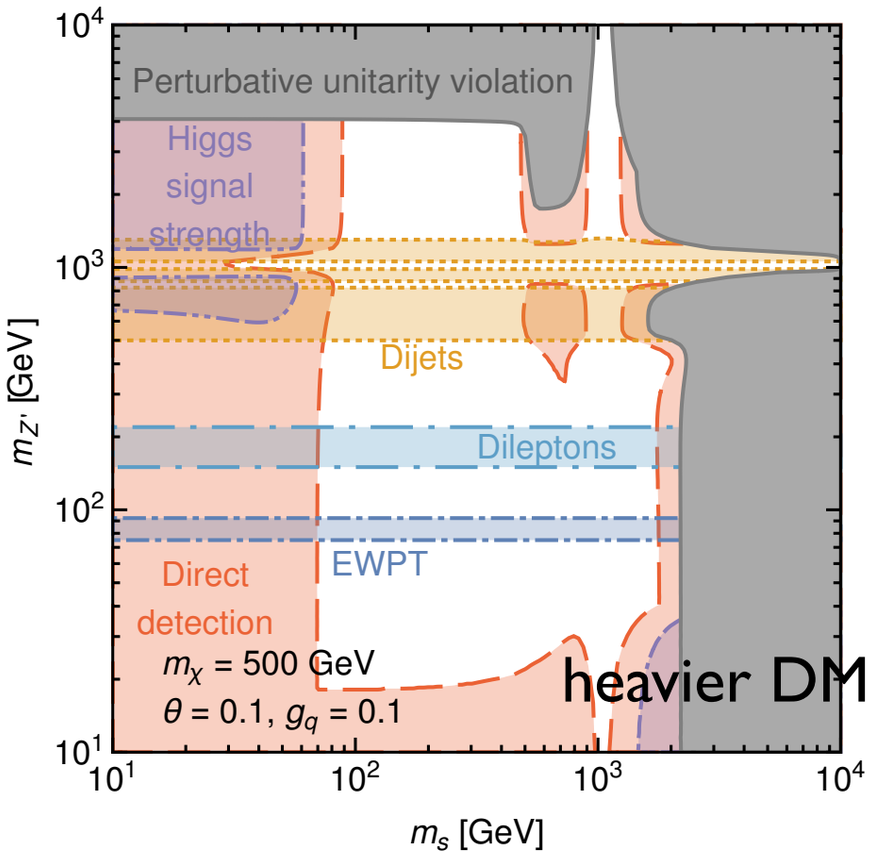
Perturbative unitarity violation
Higgs signal strength
Dijets
Dileptons
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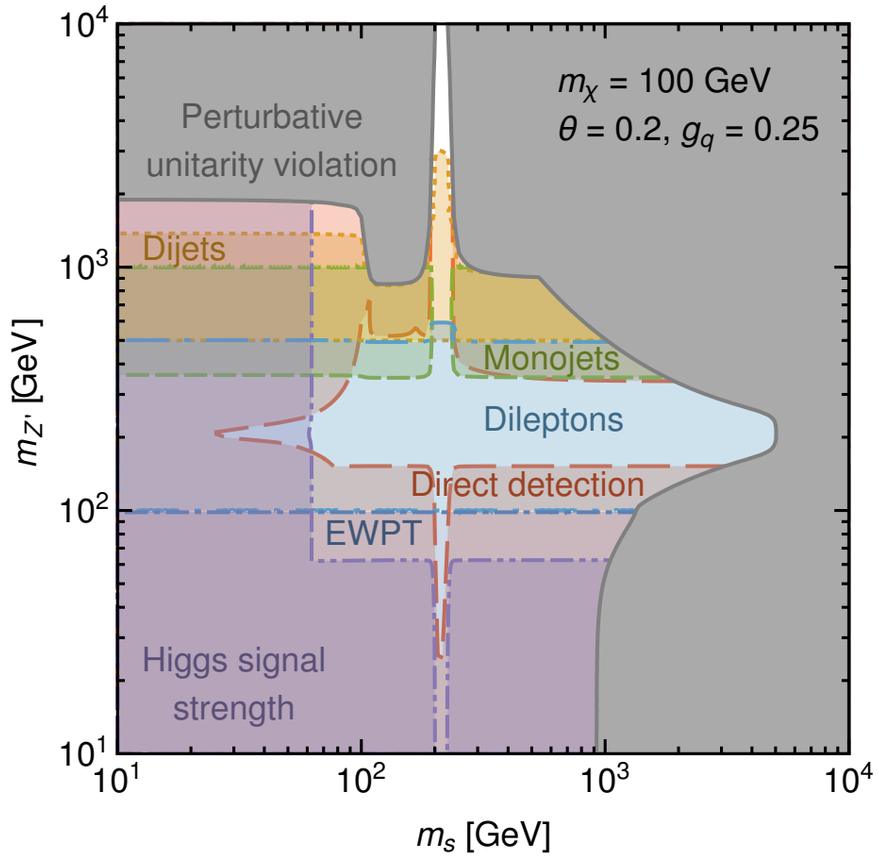
Direct detection
m_χ = 500 GeV
θ = 0.1, g_q = 0.1
heavier DM
$m_{Z'}$ [GeV]
m_s [GeV]


m_χ = 100 GeV
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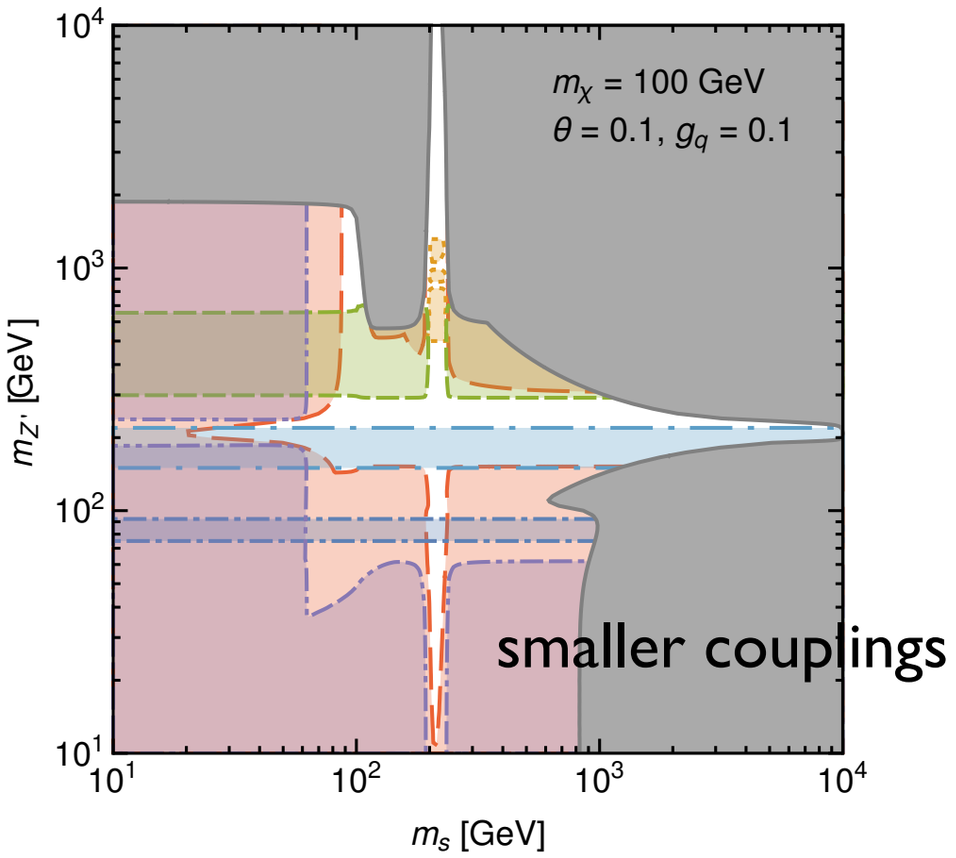
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θ = 0.1, g_q = 0.1
smaller couplings
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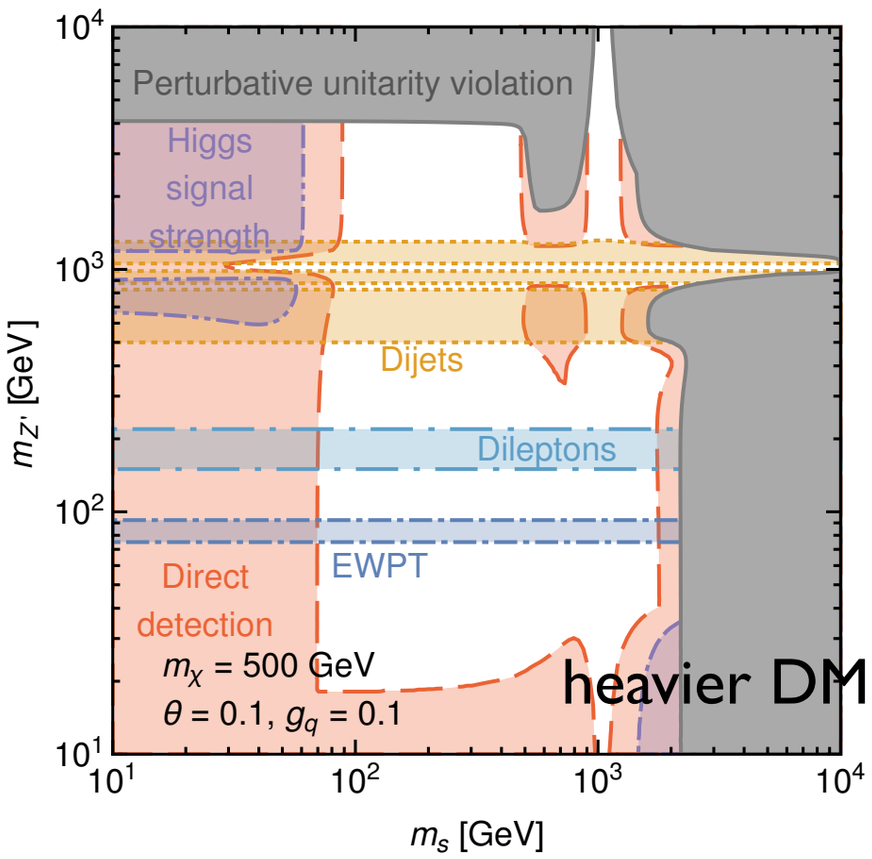
m_s [GeV]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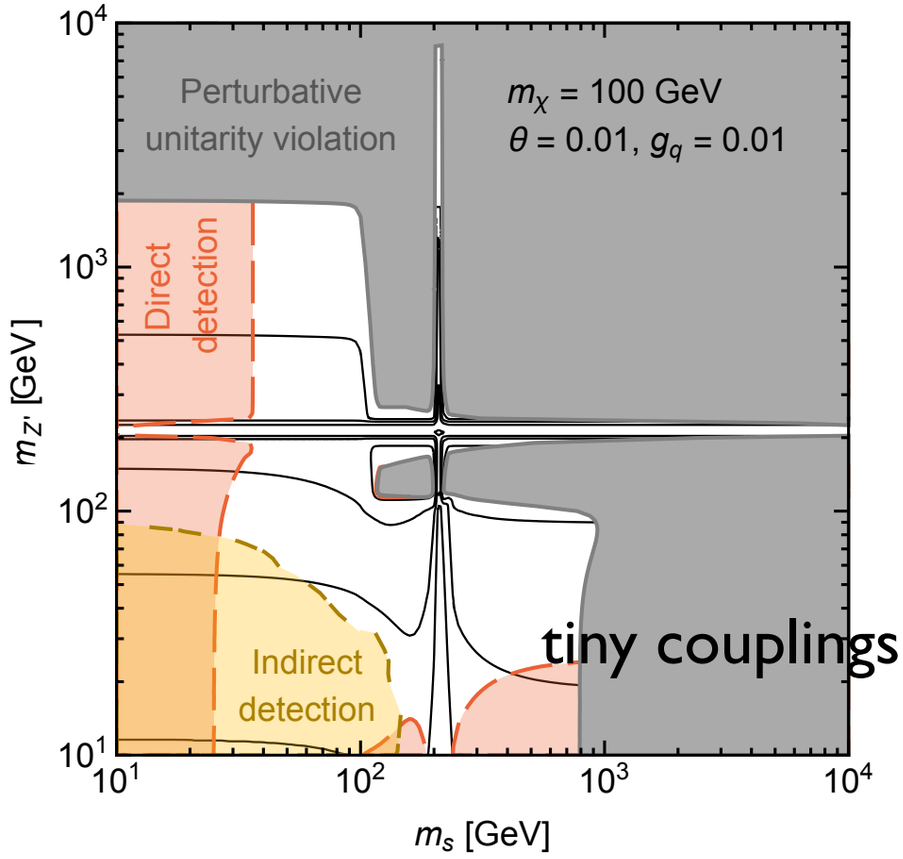
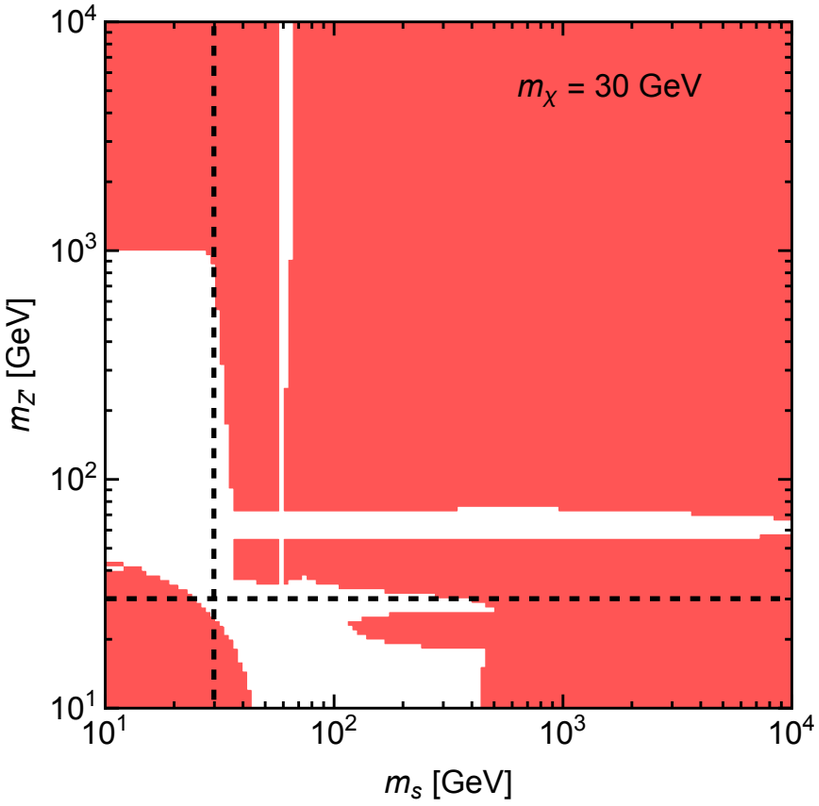
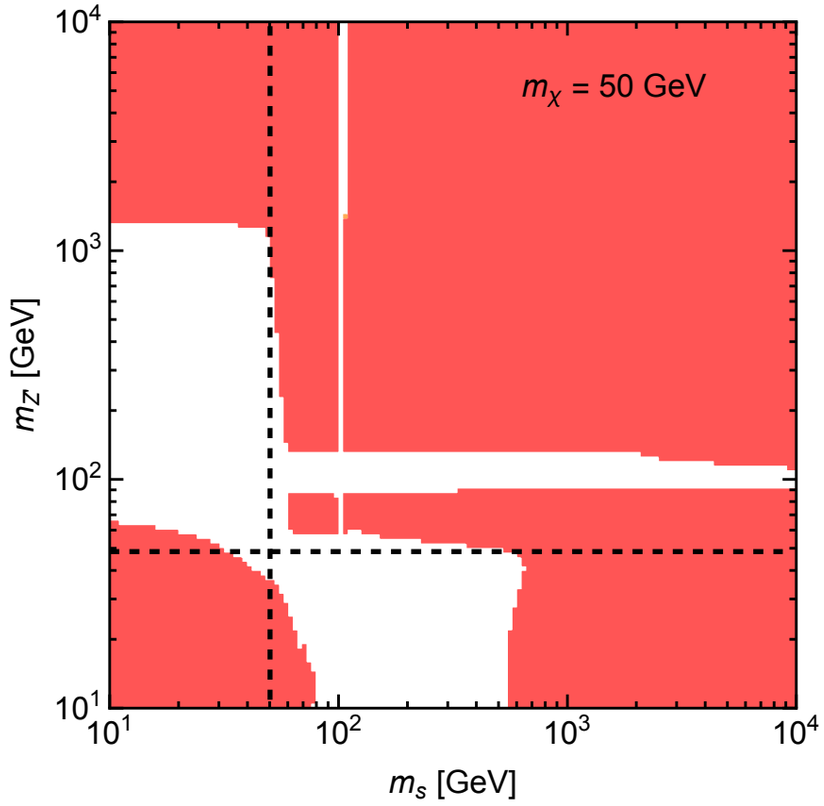
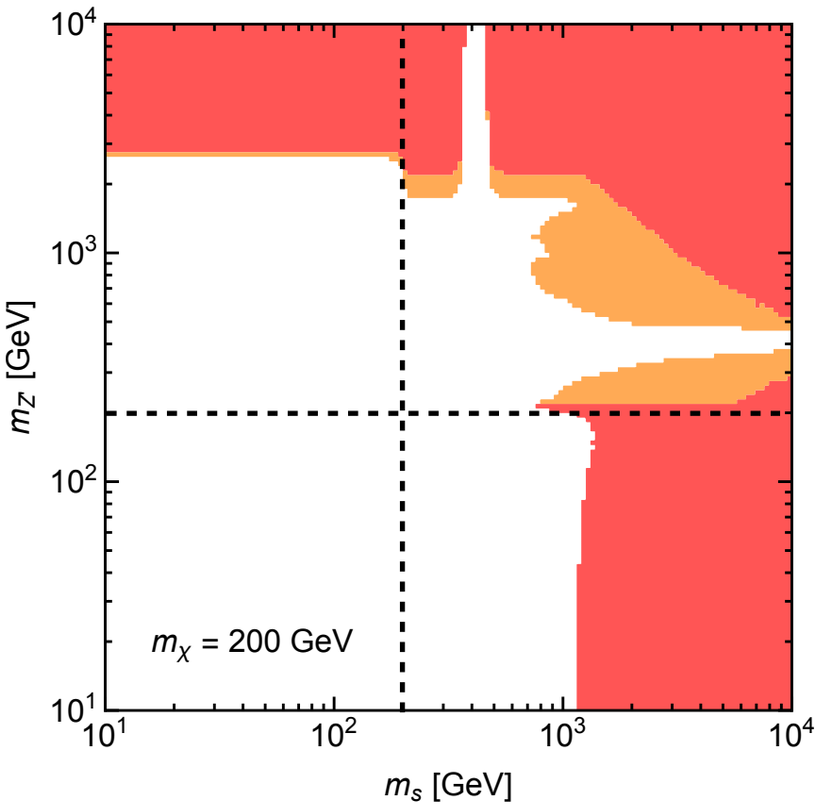
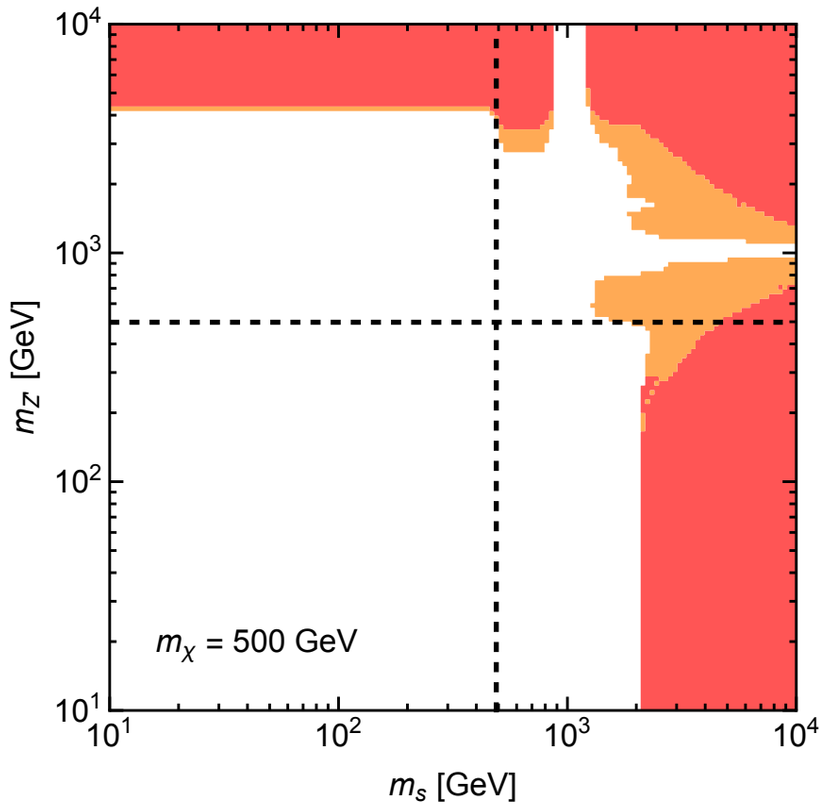

Perturbative unitarity violation
m_χ = 100 GeV
θ = 0.01, g_q = 0.01
Direct detection
Indirect detection
tiny couplings
$m_{Z'}$ [GeV]
m_s [GeV]

global parameter scan









- constraints weaken somewhat for heavier DM