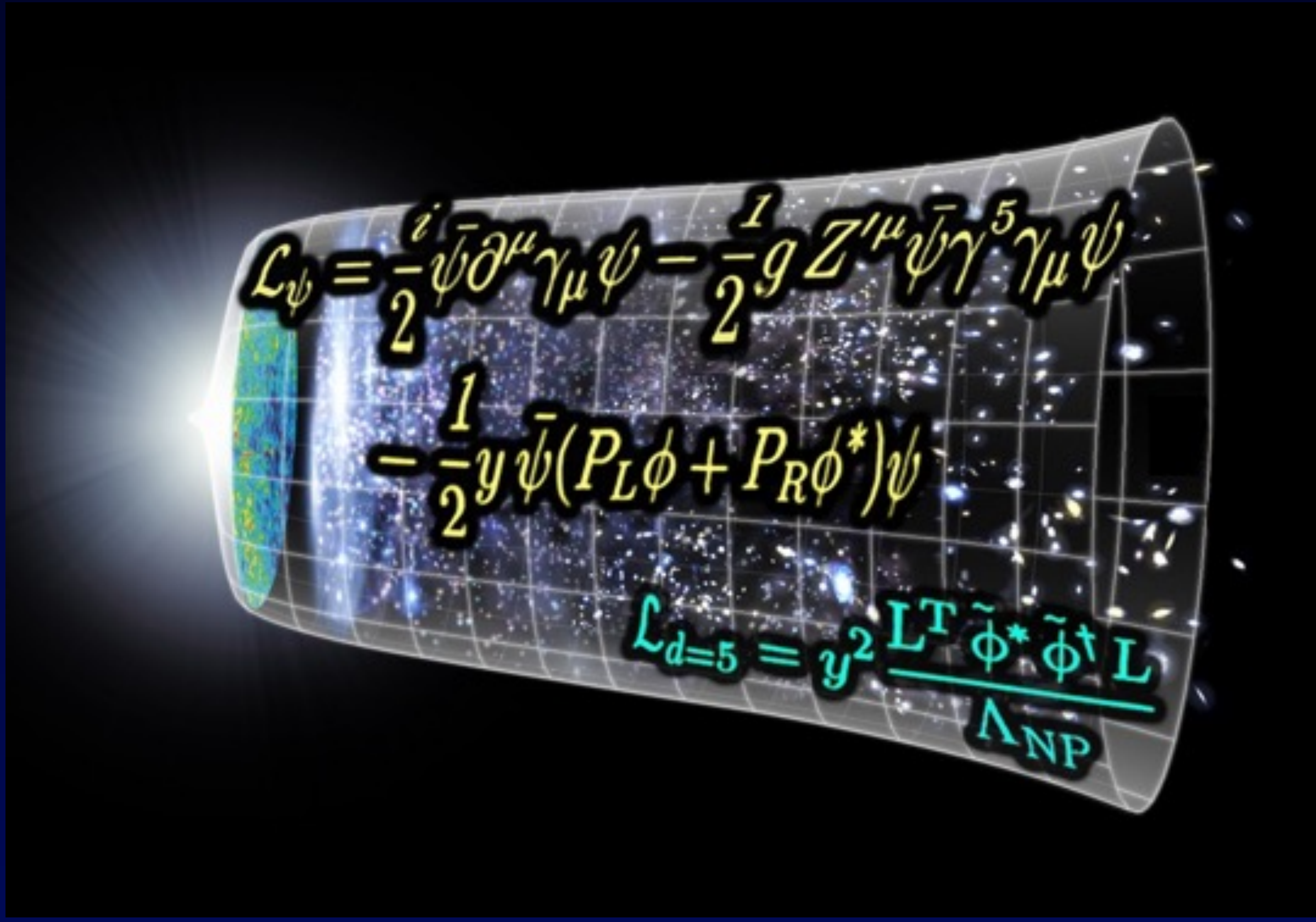
Theoretical Astroparticle Physics

KSETA Plenary meeting
Durbach, Feb. 22-24, 2016

Thomas Schwetz-Mangold

KIT
Karlsruher Institut für Technologie



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Cornering WIMP Dark Matter

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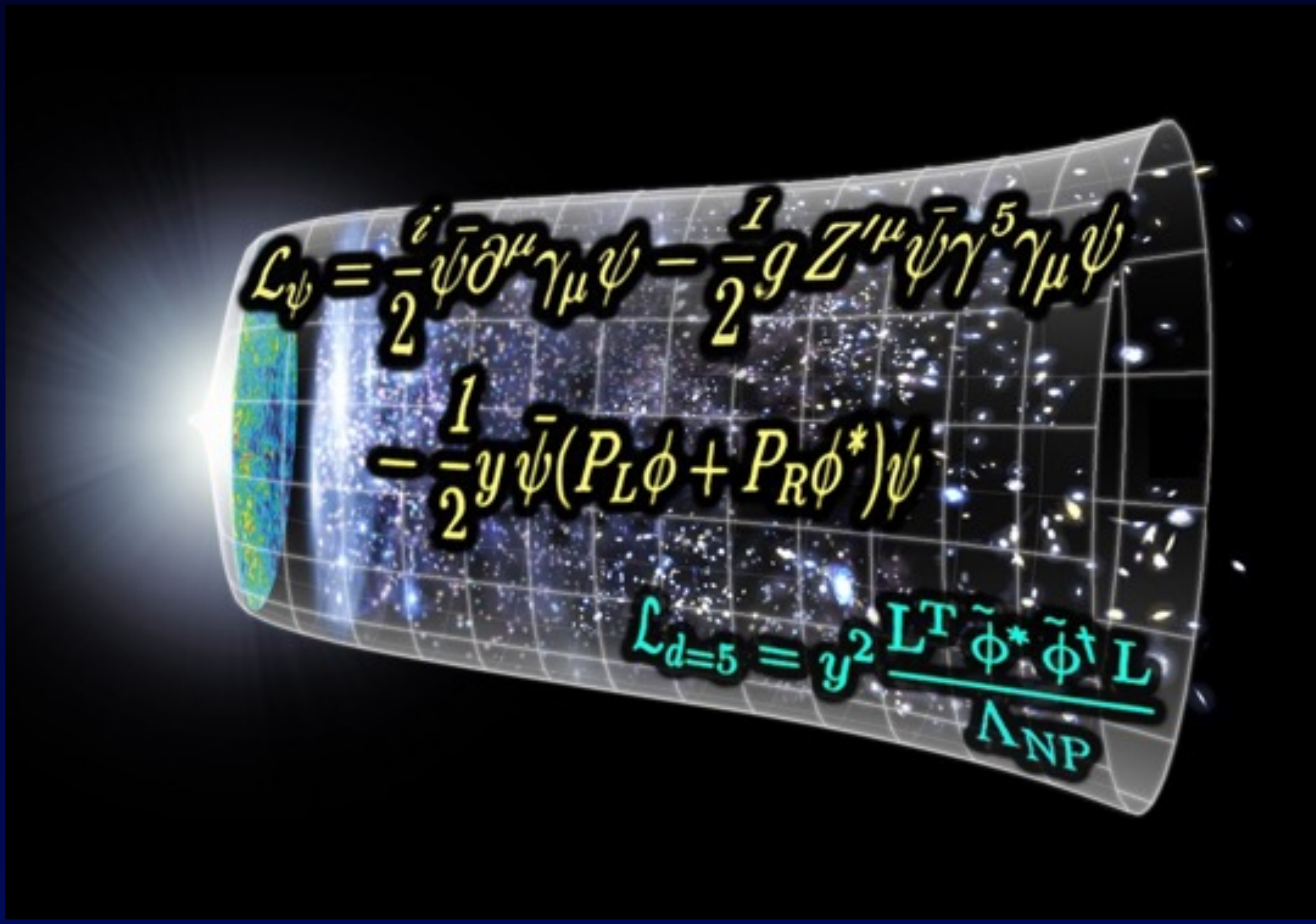

Why do we need dark matter?

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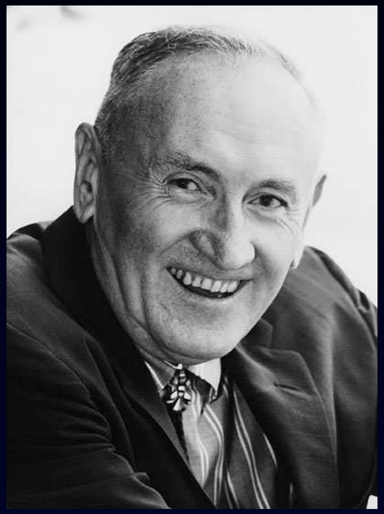
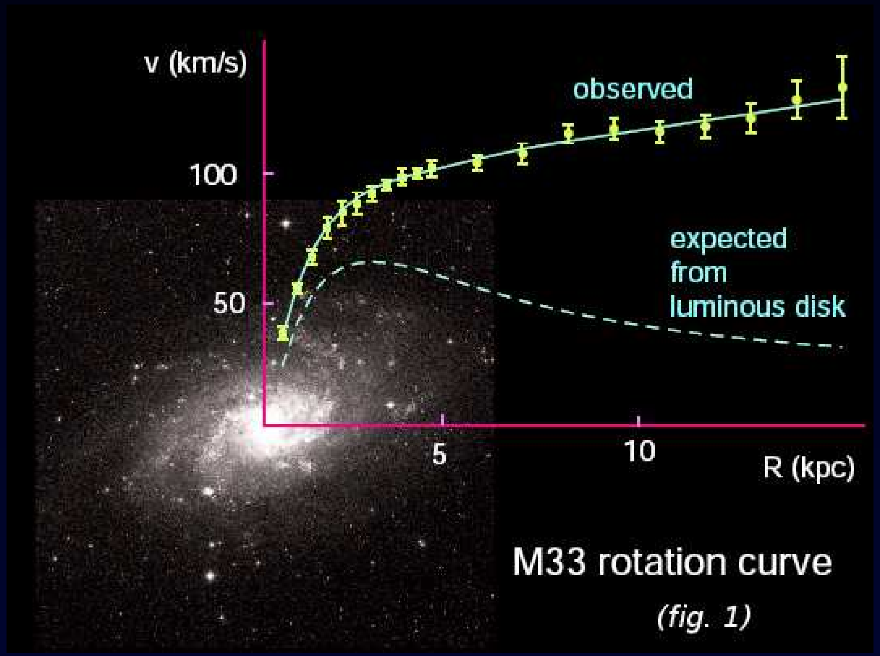
galaxies and galaxy clusters seem
to contain much more gravitating
matter than luminous matter

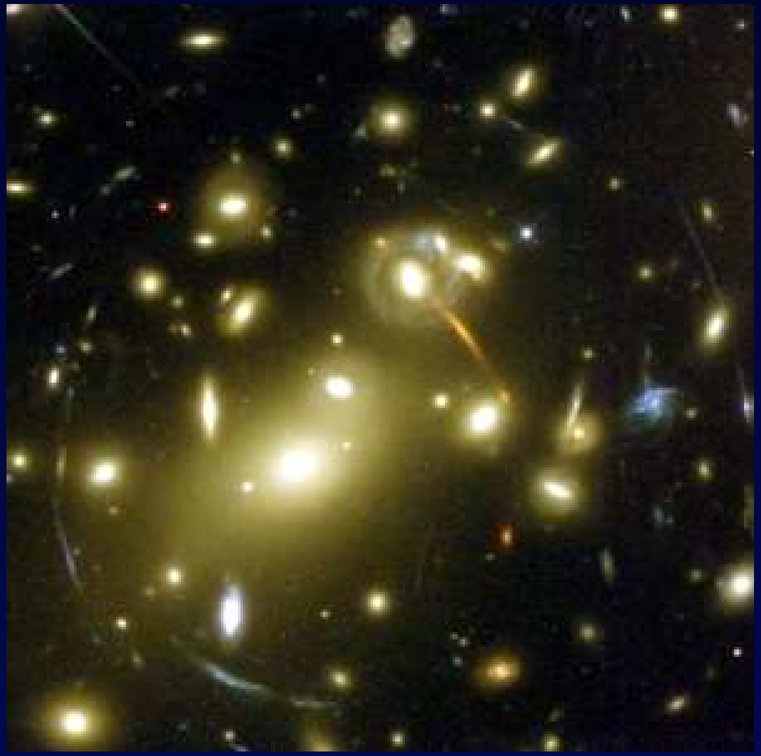
Missing matter in galaxy clusters and galaxies



F. Zwicky 1933
virial theorem
applied to
galaxy clusters

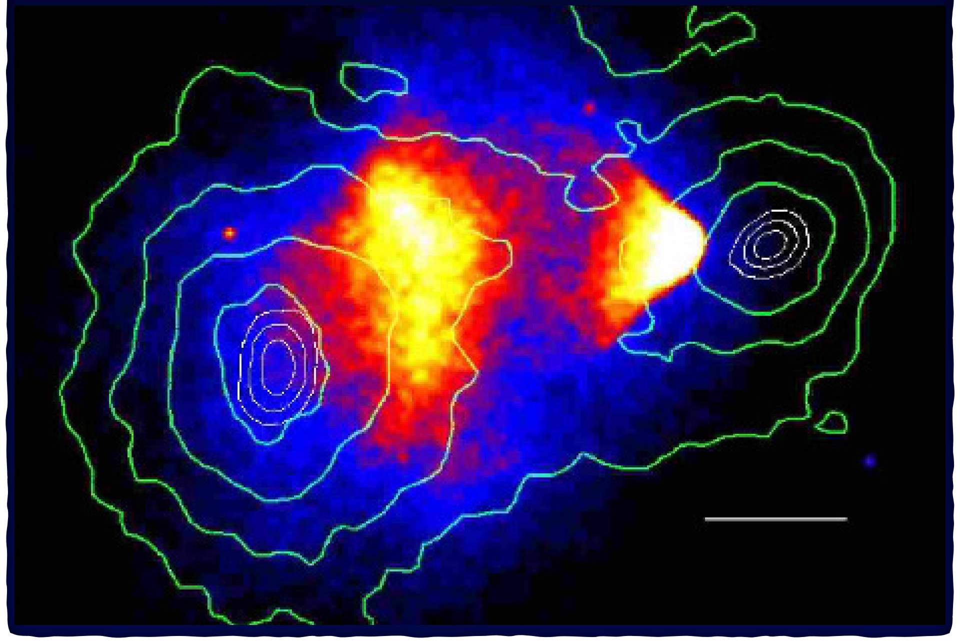
rotation velocities in galaxies



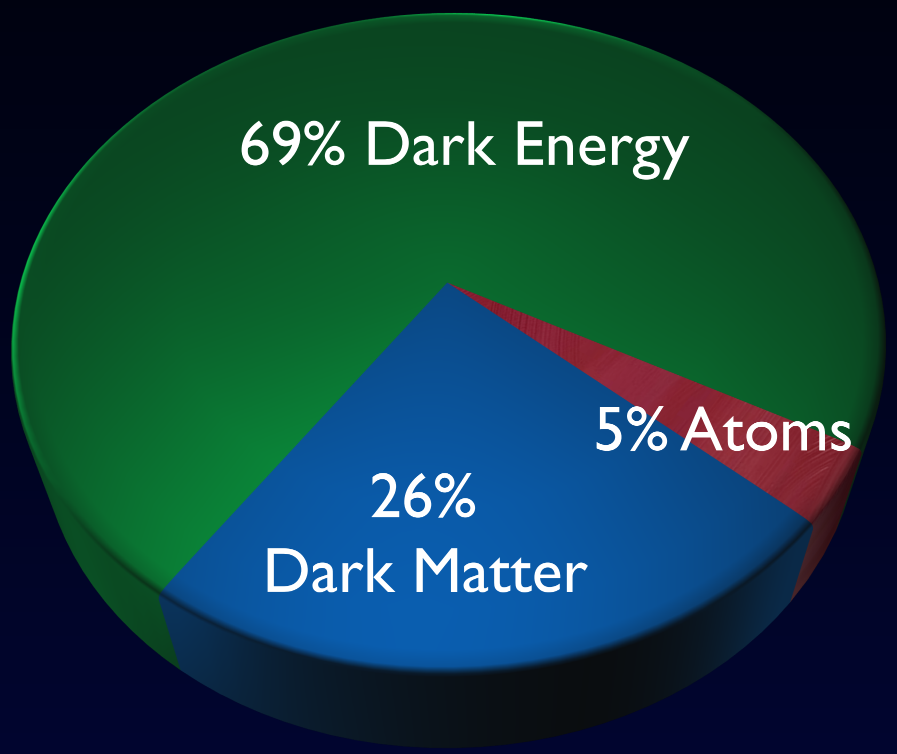


gravitational
lensing of
galaxy
clusters

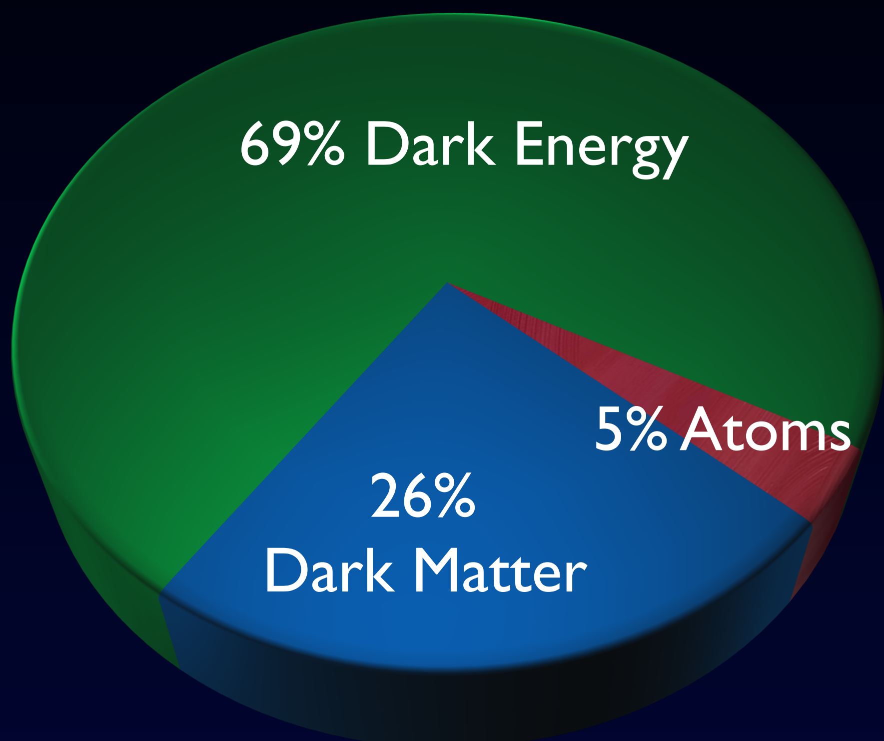
galaxy cluster mergers



Cosmological evidence for DM



Cosmological evidence for DM



ΛCDM fit to CMB + BAO

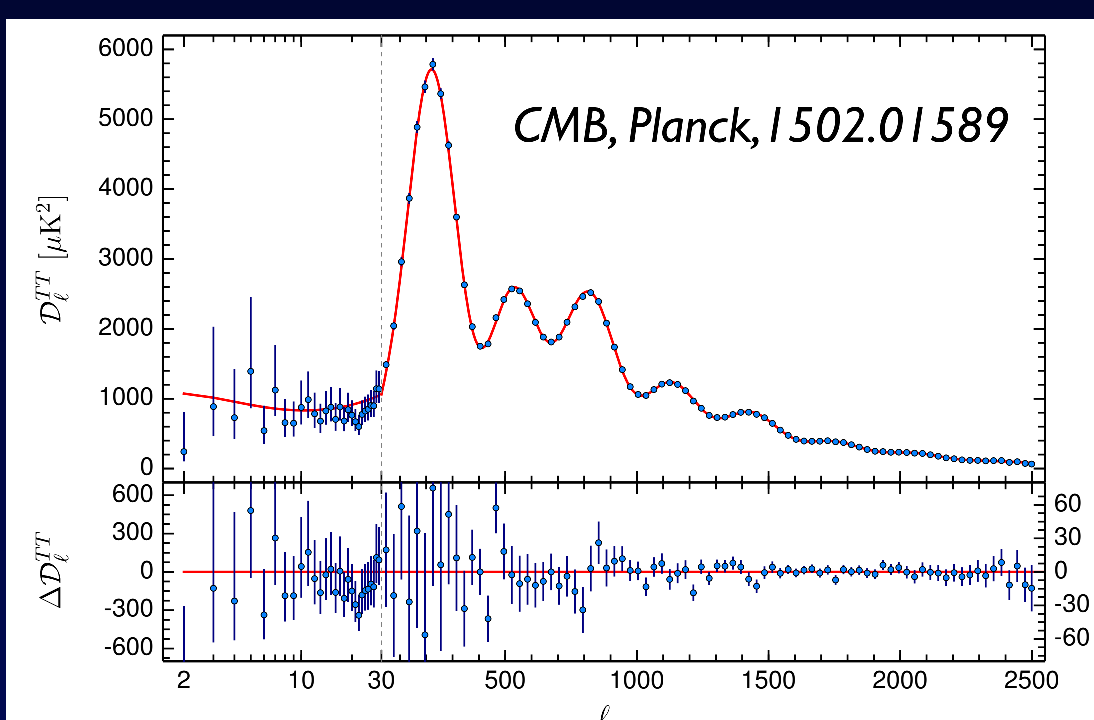
1502.01589

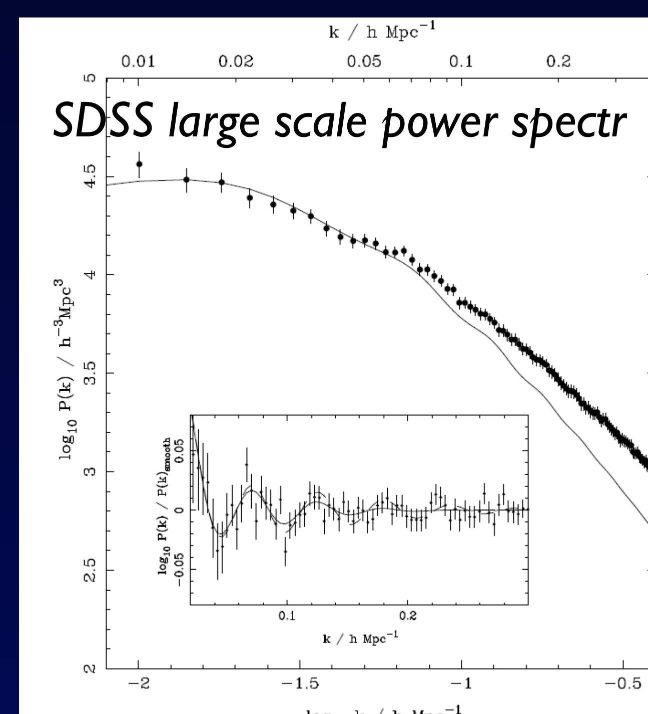
$$\Omega_B h^2 = 0.02230 \pm 0.00014$$

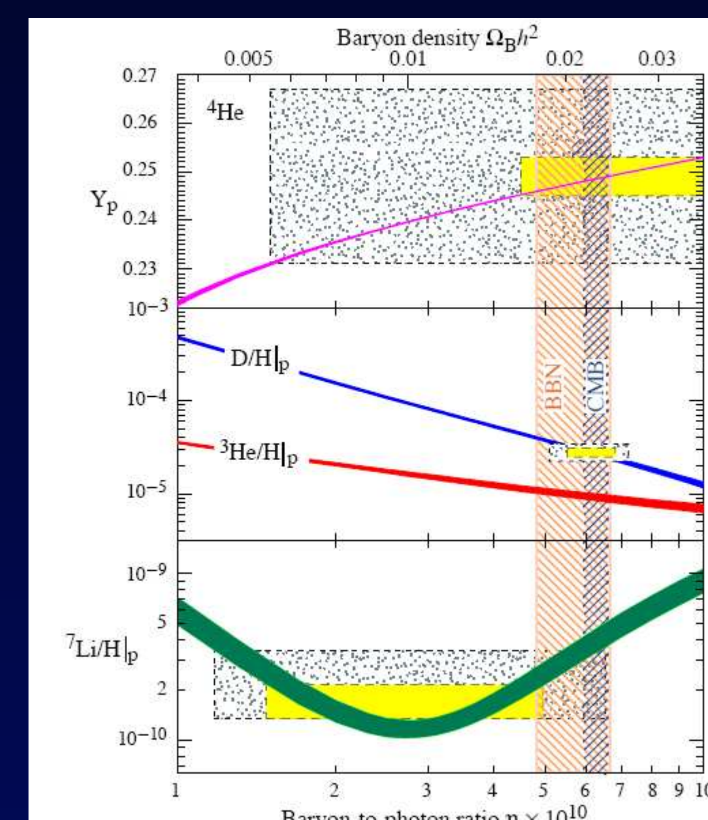
$$\Omega_C h^2 = 0.1188 \pm 0.0010$$

$$\Omega_\Lambda = 0.6911 \pm 0.0062$$

$$h = 0.6774 \pm 0.0046$$

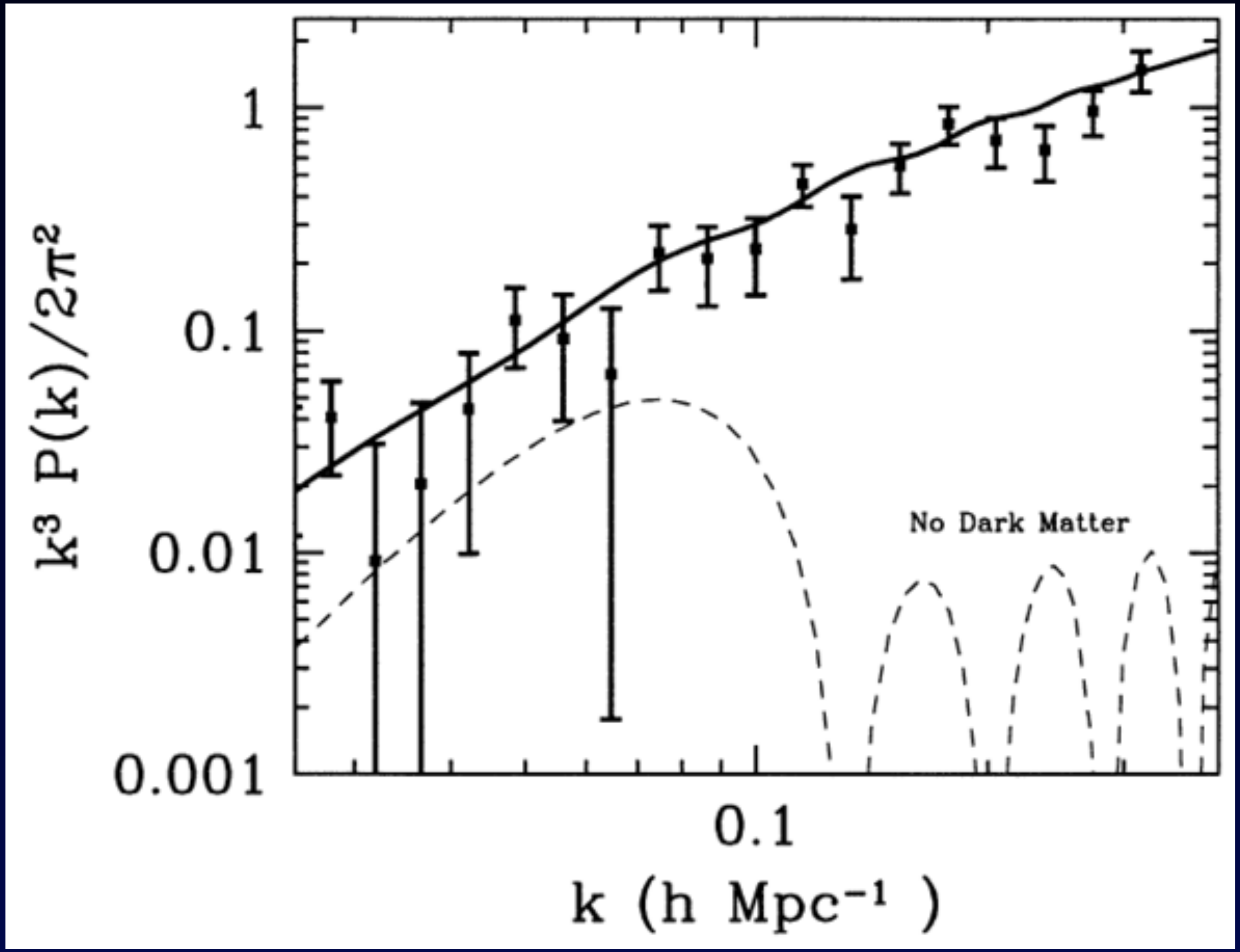






Cosmological evidence for DM

need DM to grow enough structure



S. Dodelson

Challenge for particle physics

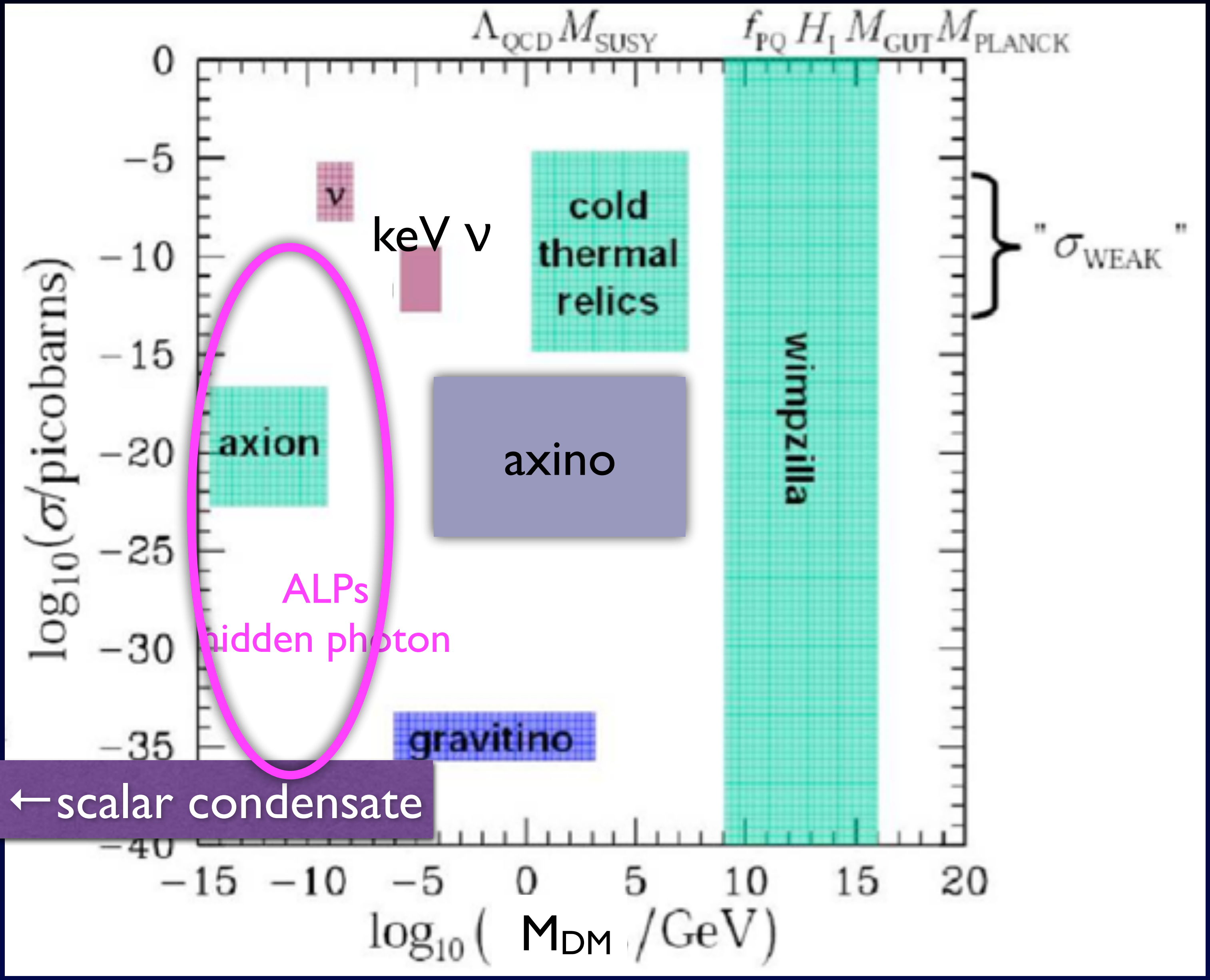
- within the Standard Model there is no suitable particle to provide the DM
  → need new particle(s)

Challenge for particle physics

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

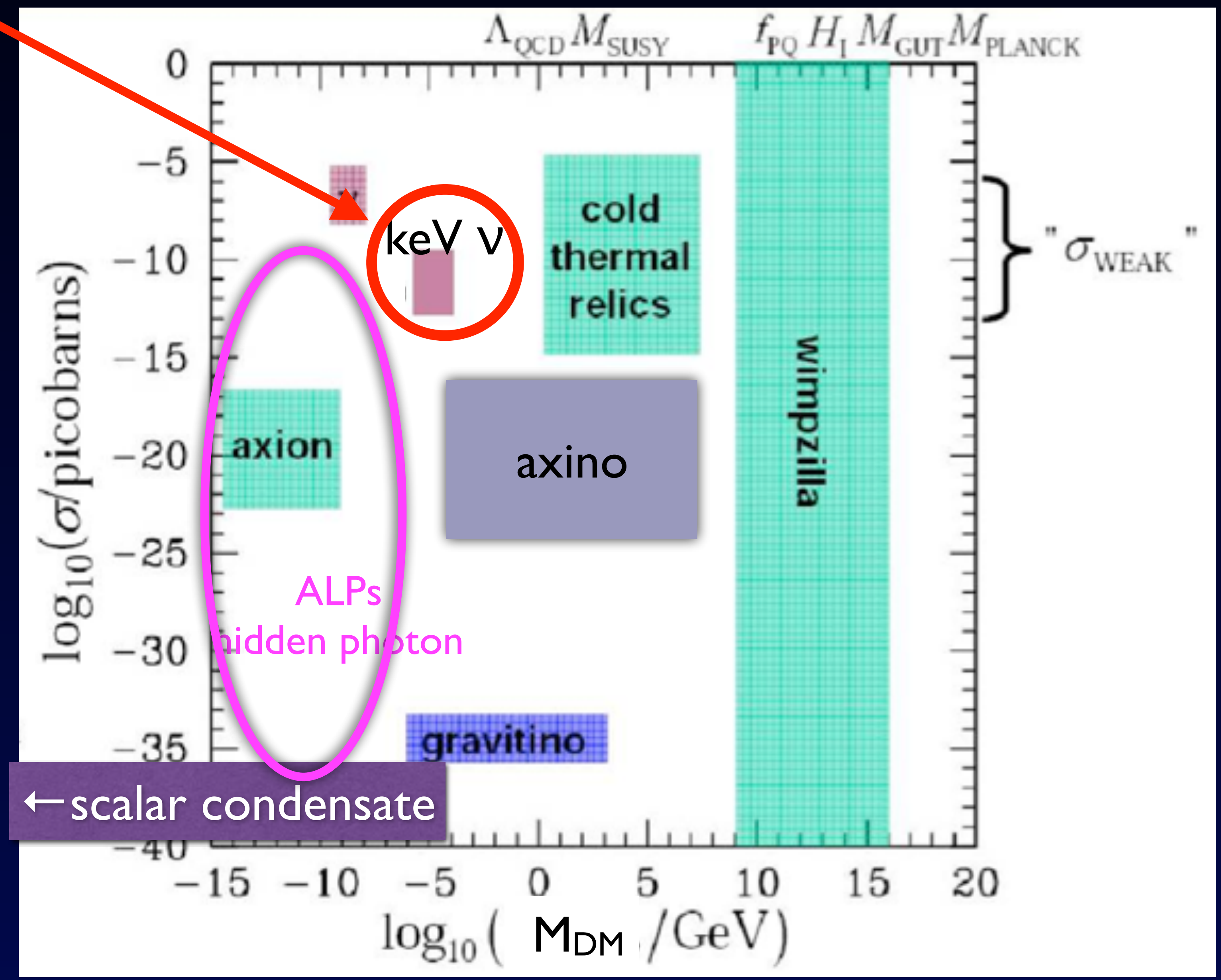
- Why is it so abundant?
- Why is it (quasi) stable?
- Is it elementary or composite?
- Is there a „dark sector“?

Challenge for particle physics



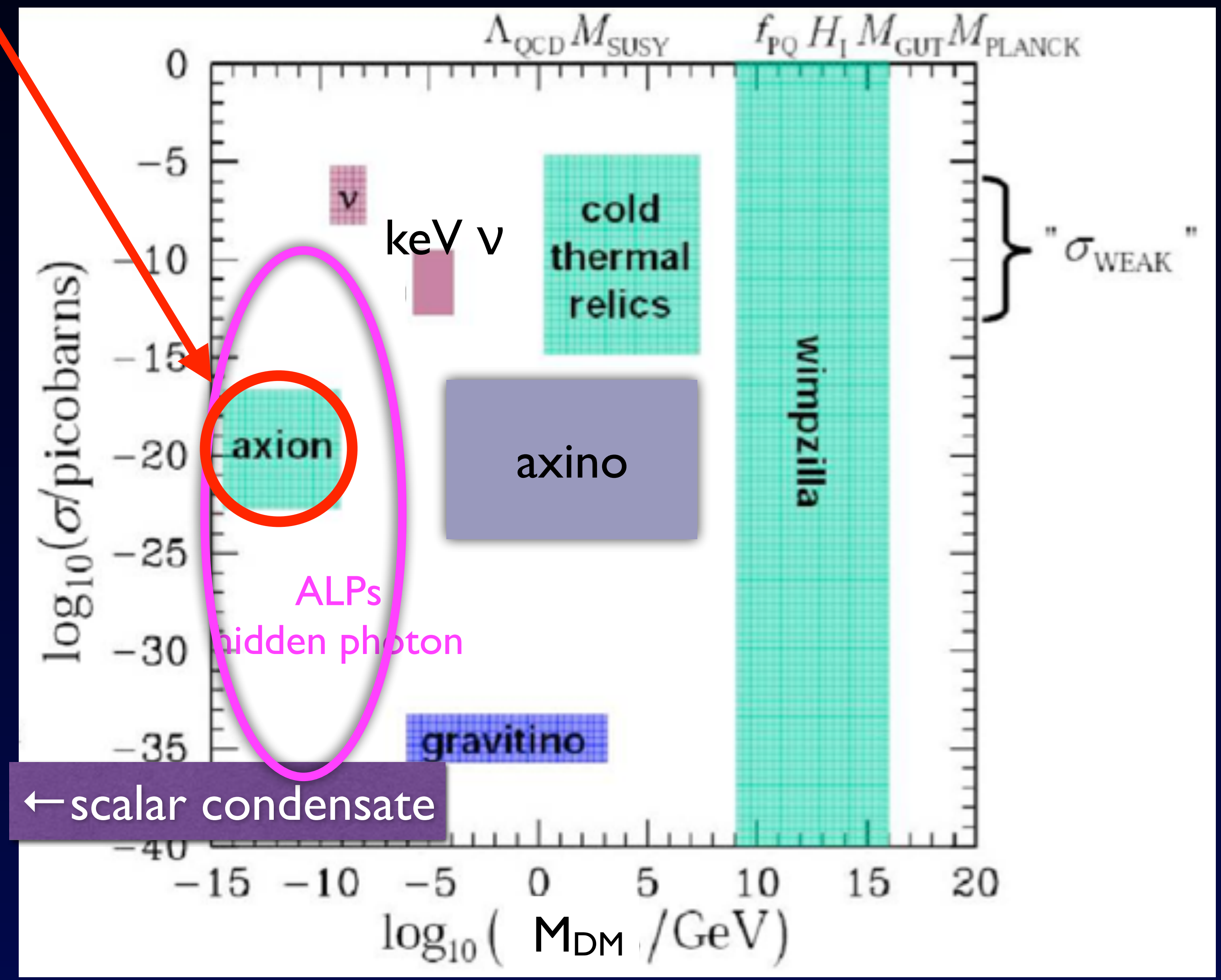
Challenge for particle physics

sterile neutrino *talk by S. Mertens*

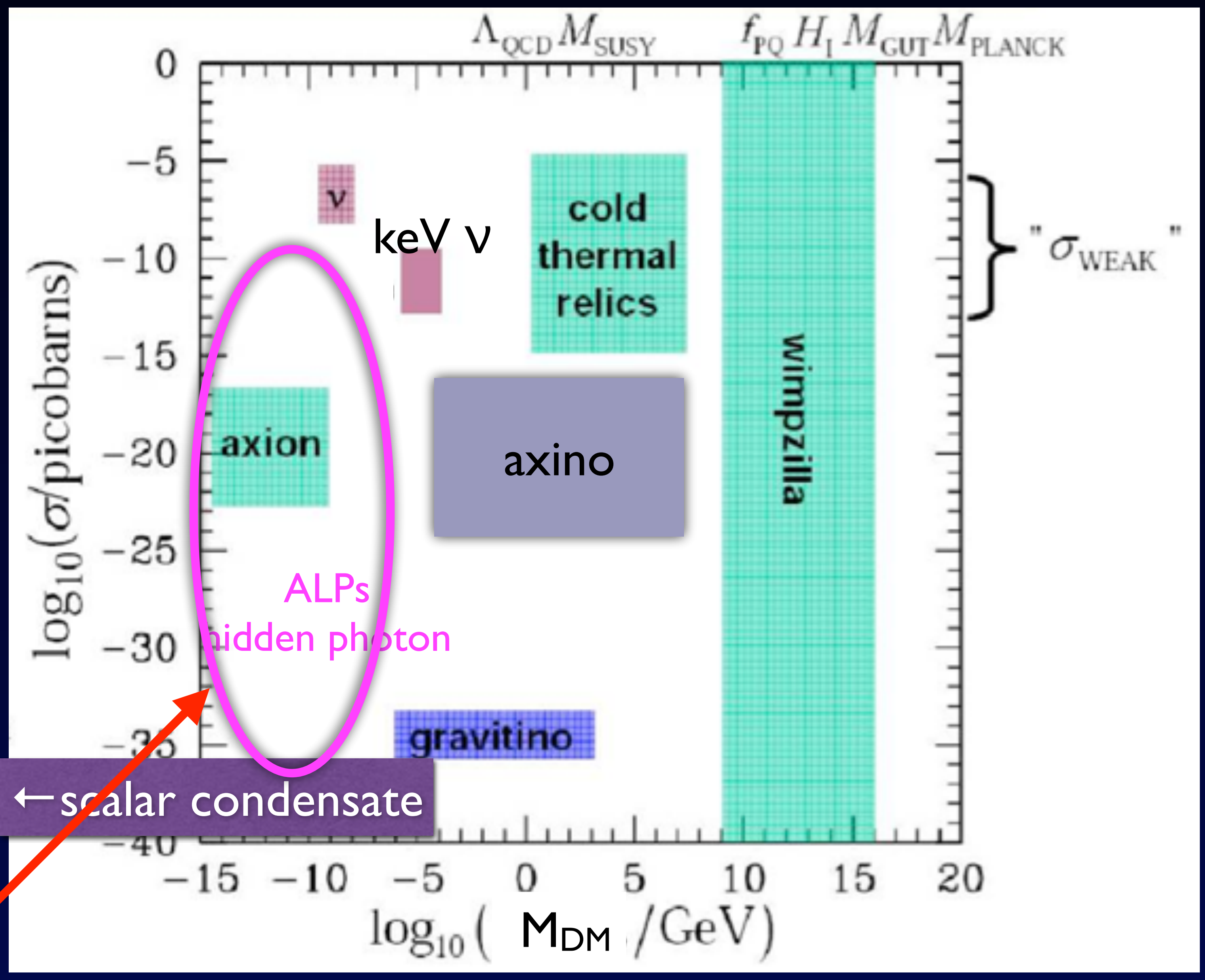


Challenge for particle physics

axion: possibly related to the strong-CP problem



Challenge for particle physics

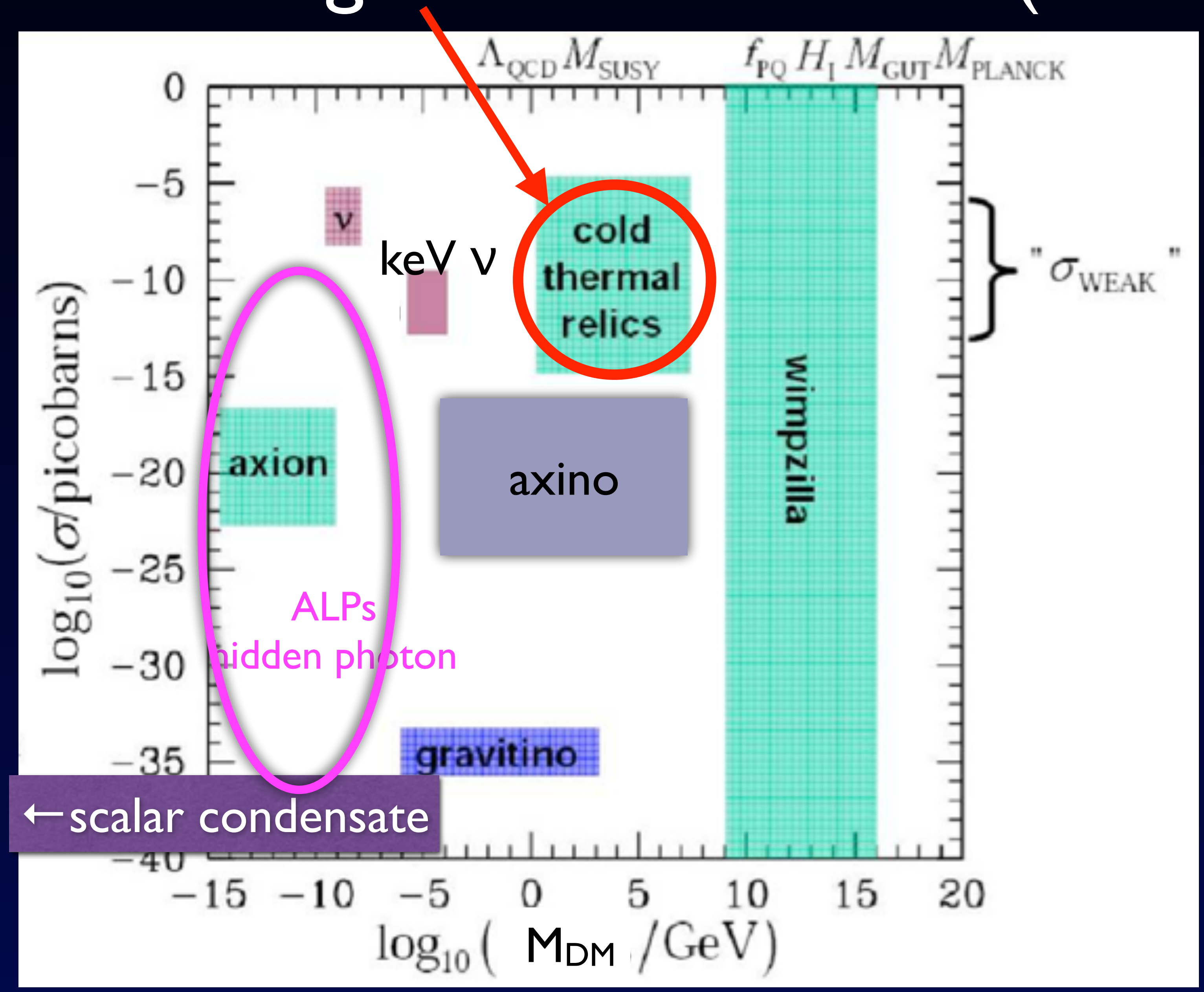


hidden photon DM: FUNK experiment at KIT

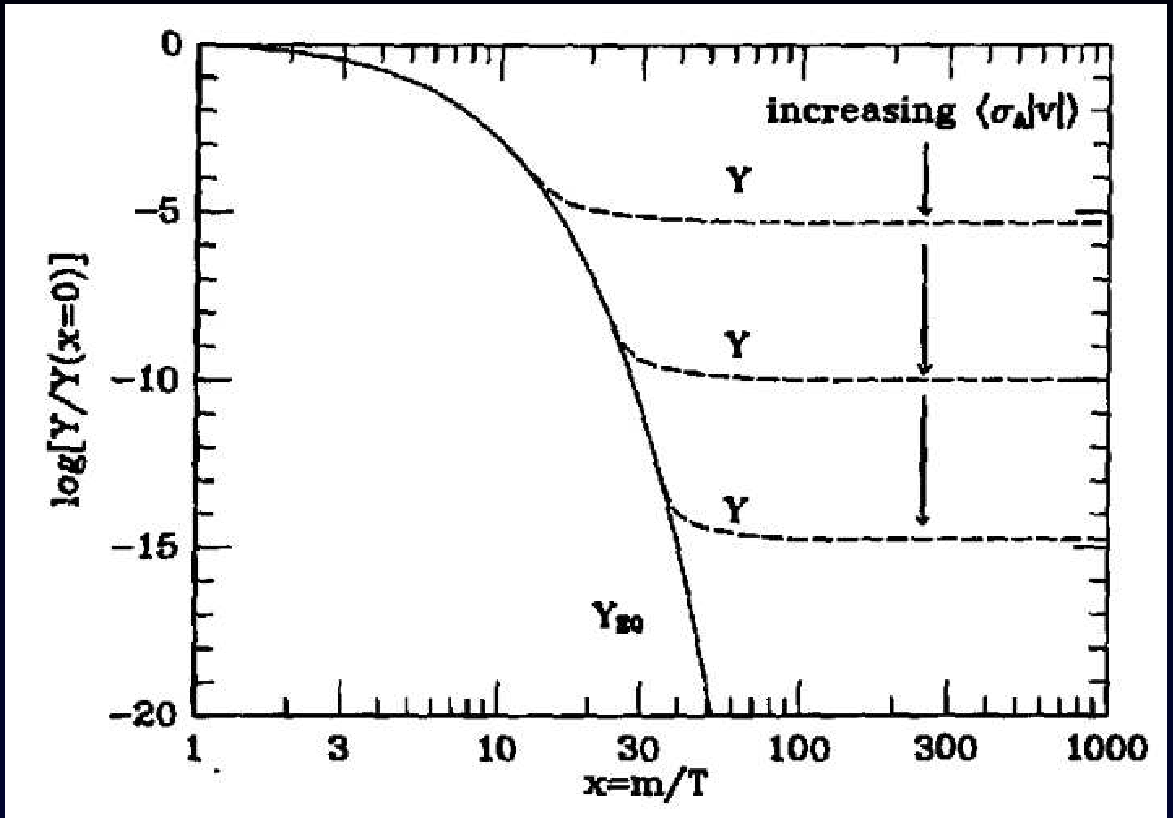
Challenge for particle physics

rest of this talk:

Weakly Interacting Massive Particles (WIMPs)



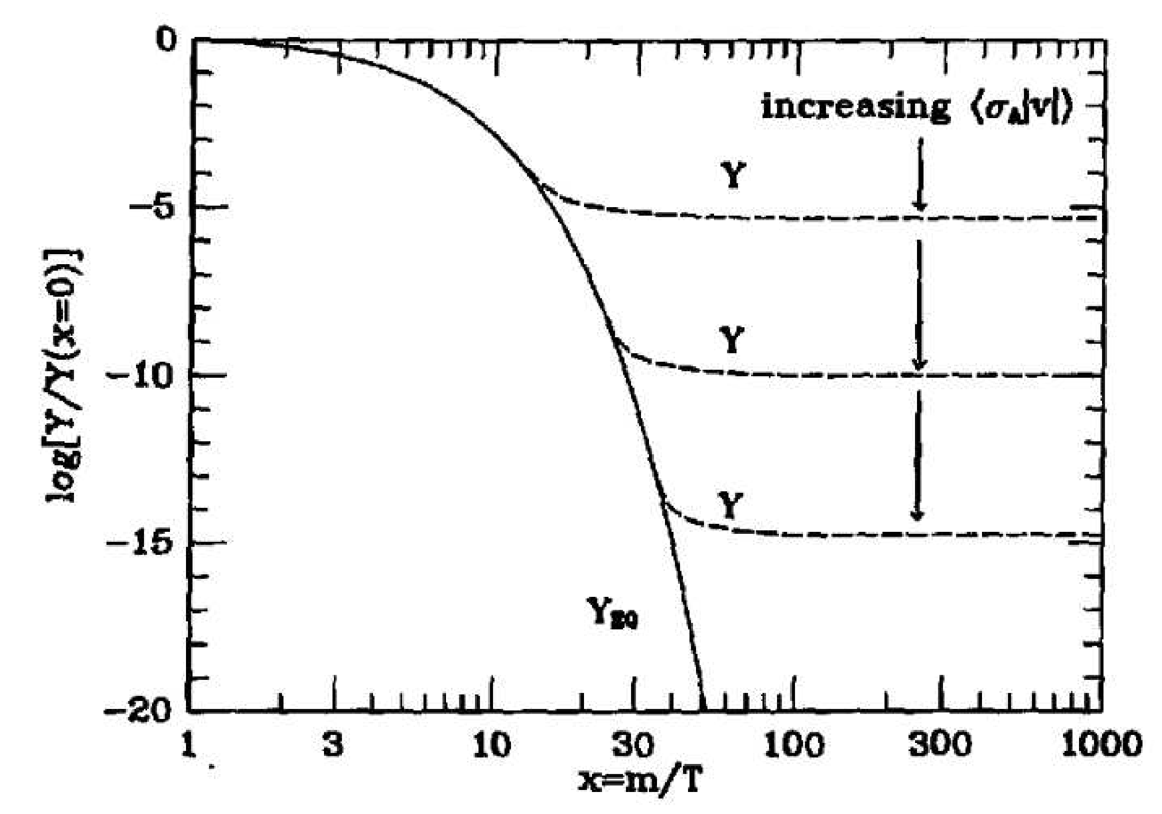
The WIMP hypothesis: thermal freeze-out



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

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

The WIMP hypothesis: thermal freeze-out



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

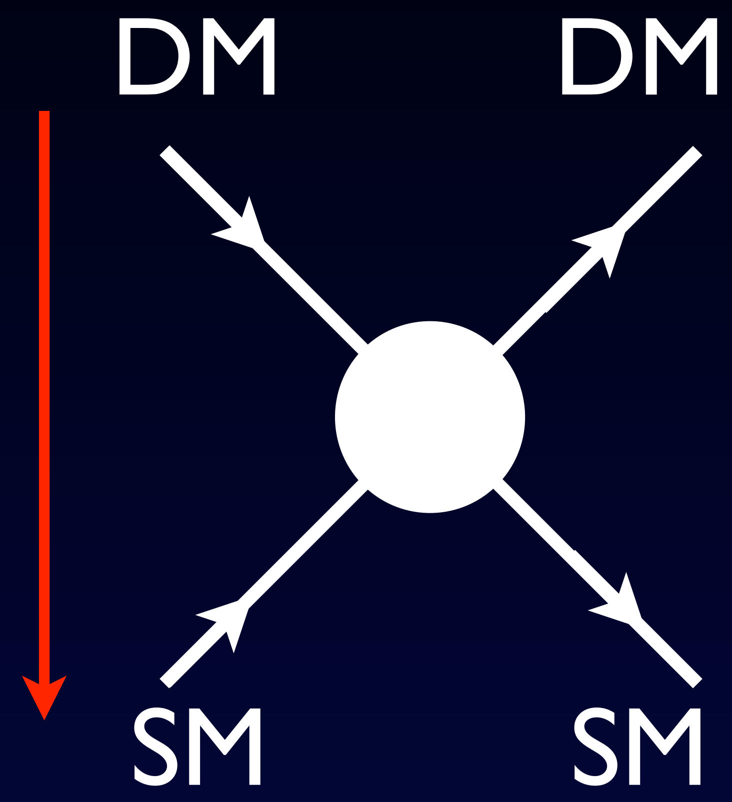
Lee, Weinberg, 1977
Bernstein, Brown, Feinberg, 1985
Scherrer, Turner, 1986

"typical" annihilation cross section:

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

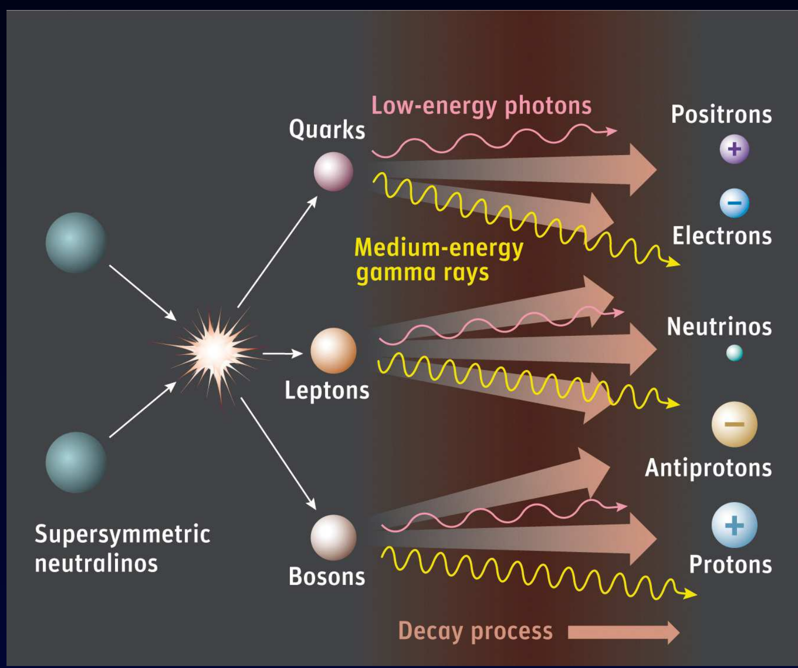
- "Weakly Interacting Massive Particle" (WIMP)
- relation with new physics at the TeV scale

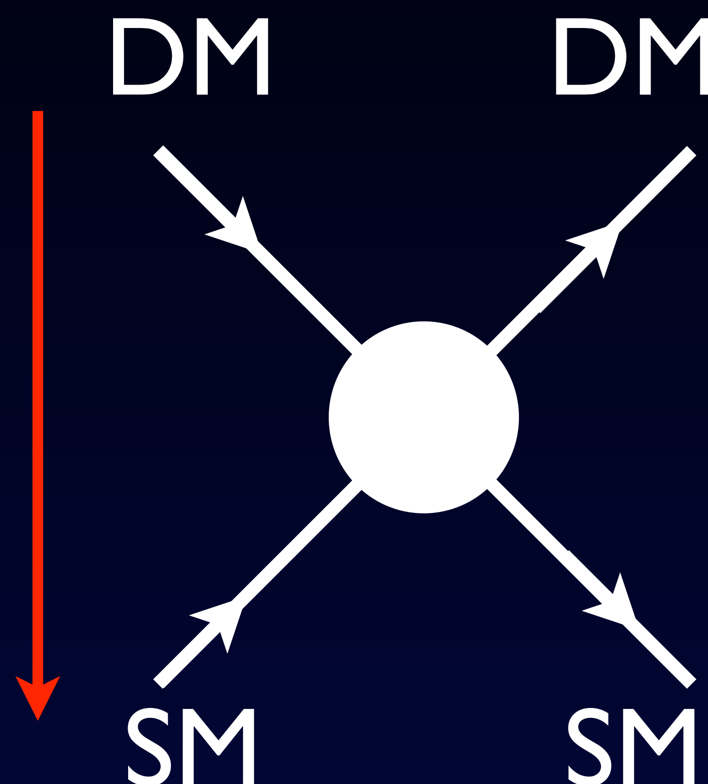
WIMP searches



WIMP searches

indirect detection

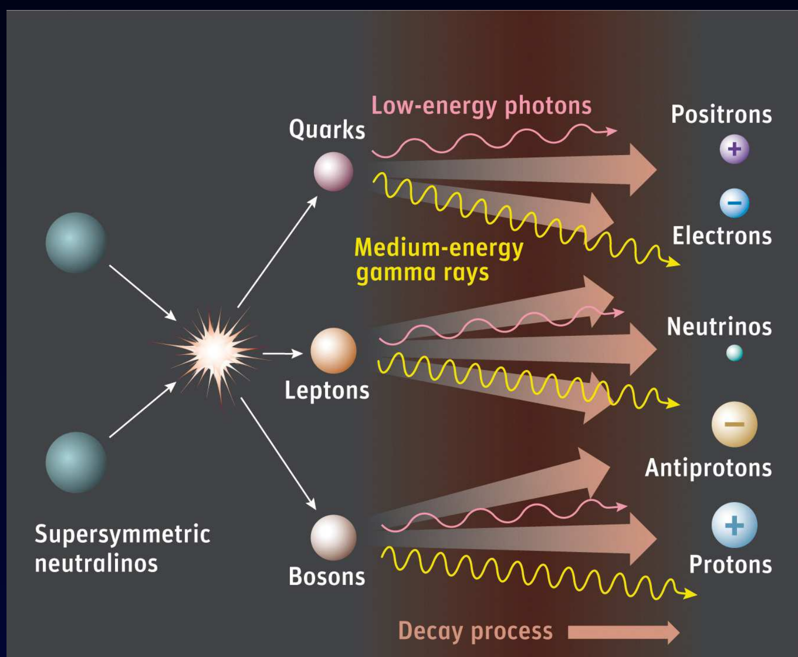




PAMELA, FERMI, AMS-2, HESS, IceCube

WIMP searches

indirect detection



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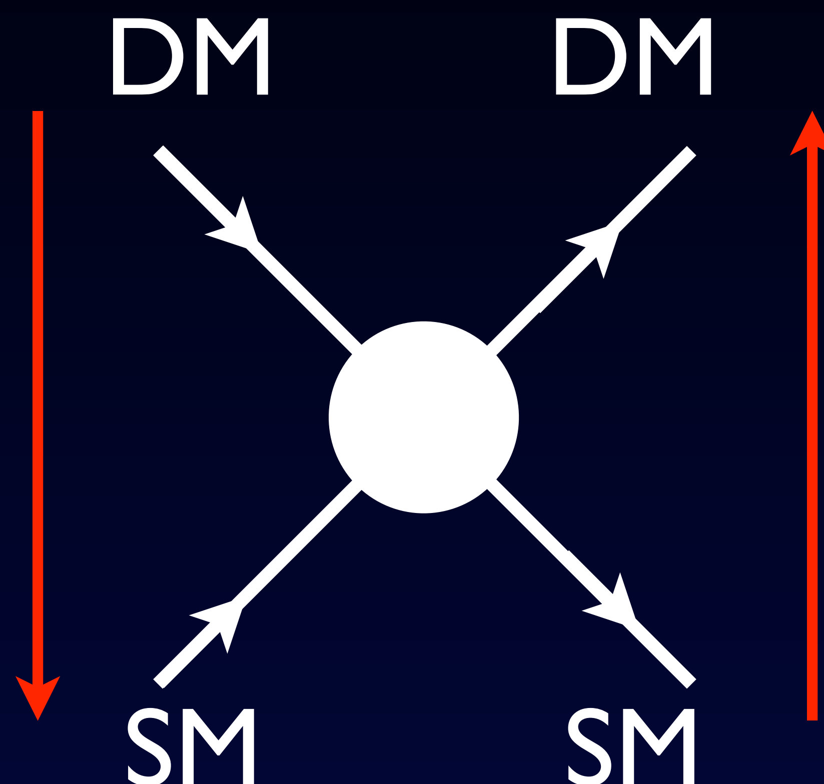
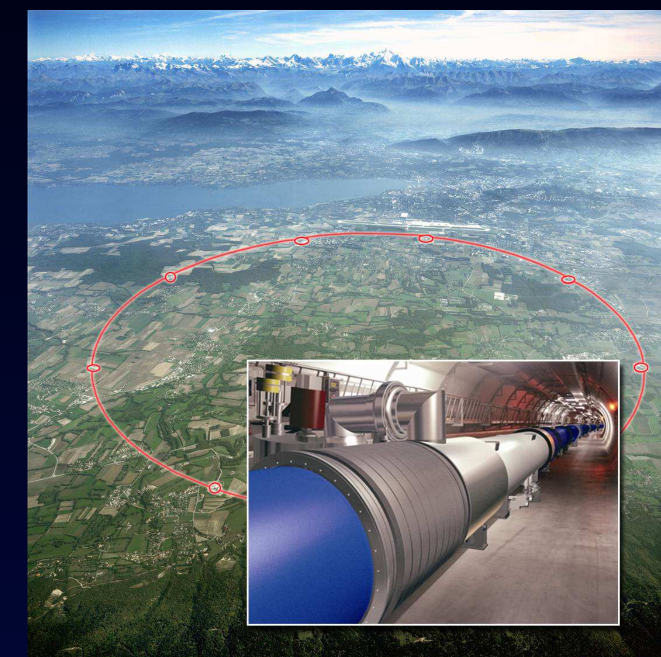


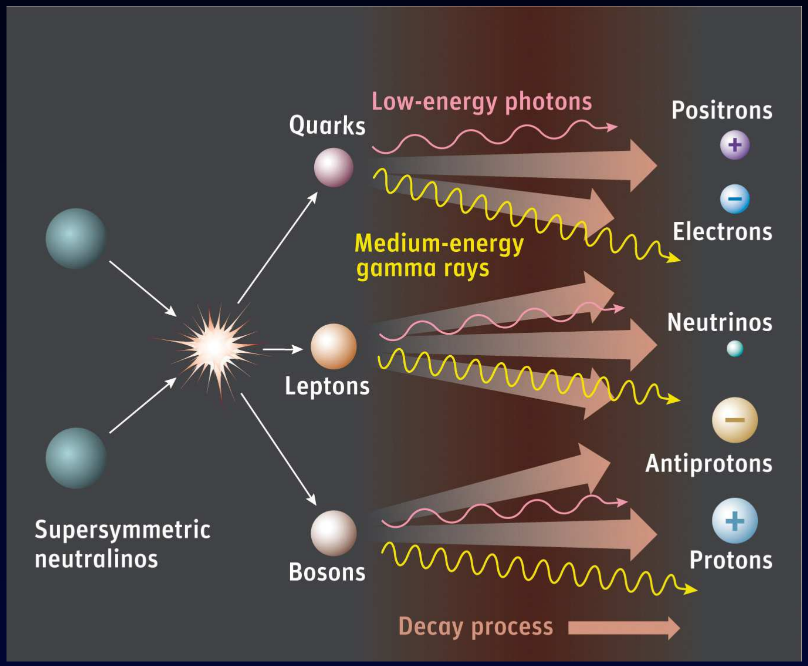
accelerators



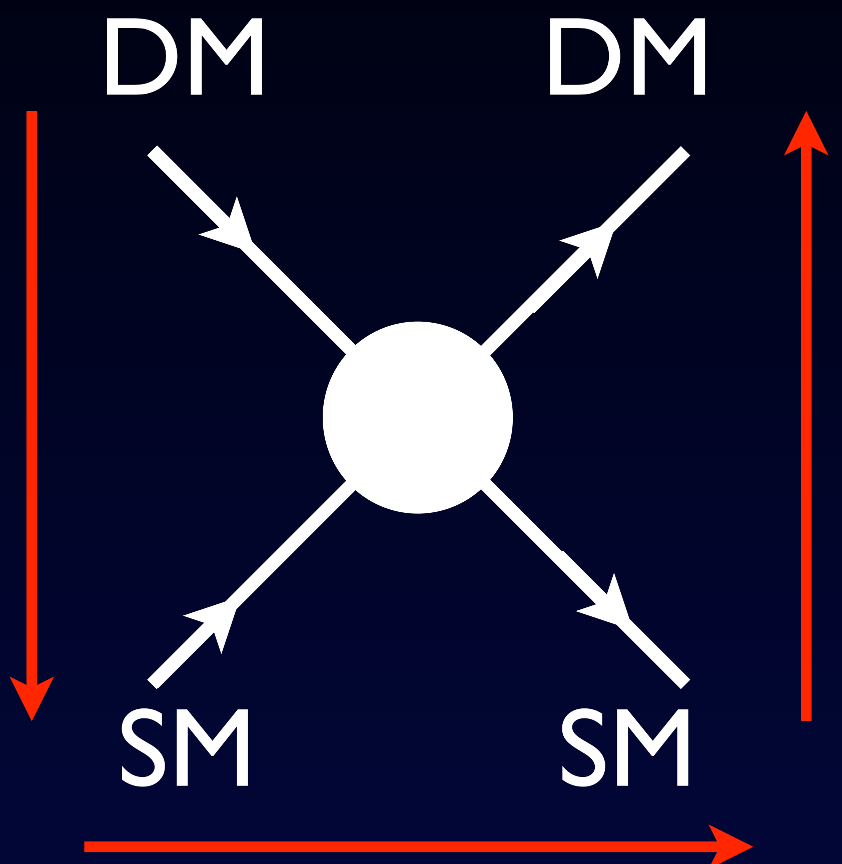
LHC

WIMP searches

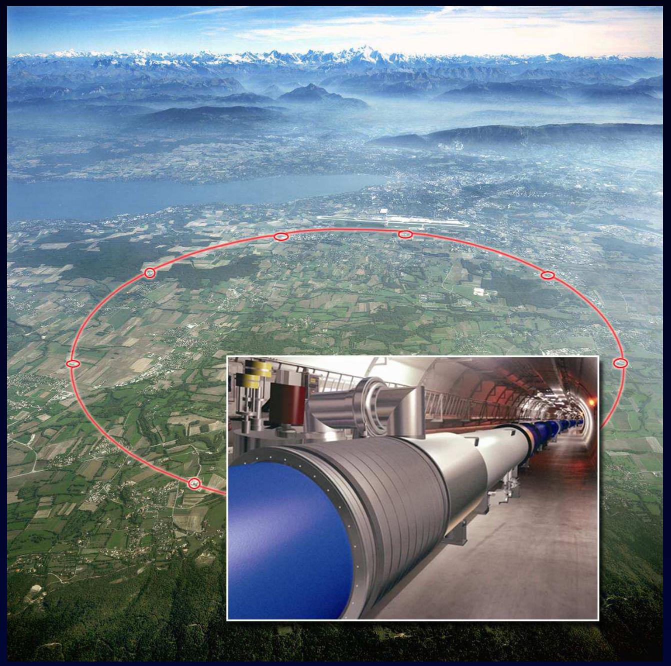
indirect detection



PAMELA, FERMI, AMS-2, HESS, IceCube

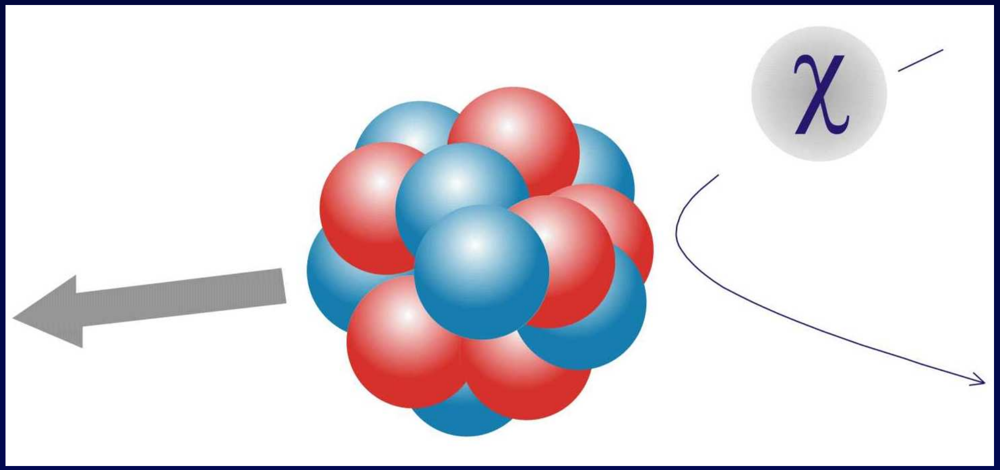


accelerators



LHC

direct detection



XENON, LUX, CDMS, Edelweiss, DAMA, CoGeNT, CRESST, PICASSO, COUPP,...

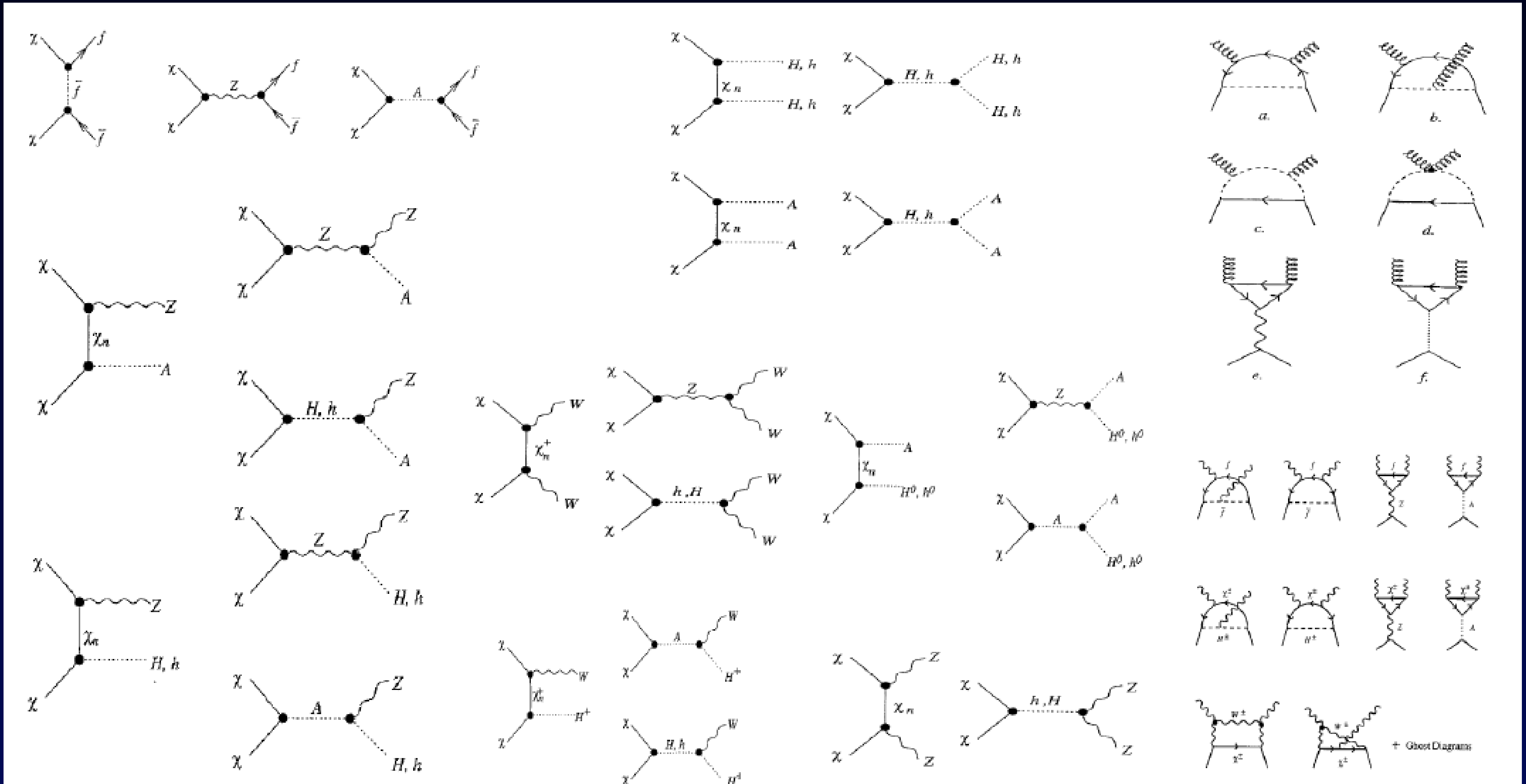
WIMP models

UV-complete models (SUSY)

WIMP models

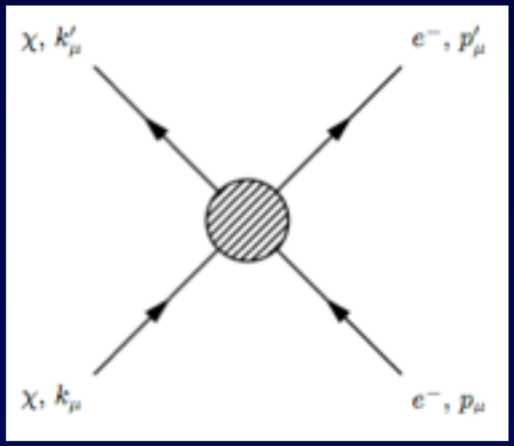
UV-complete models (SUSY)

SUSY diagrams contributing to neutralino annihilation cross sec.



WIMP models

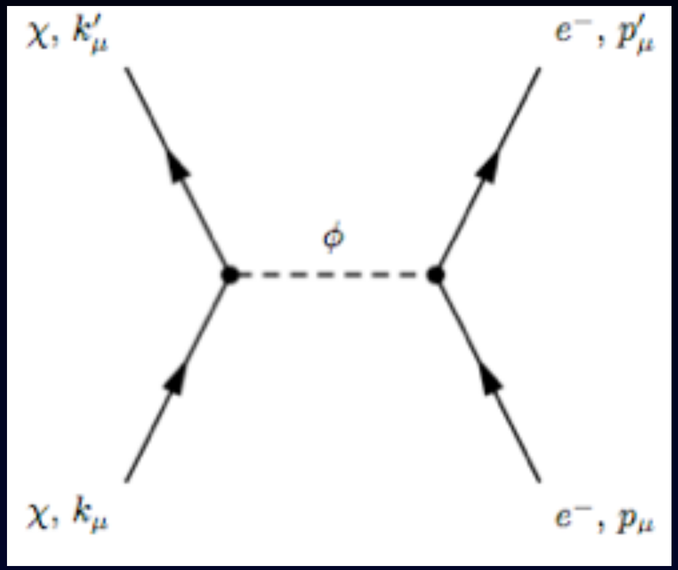
UV-complete models (SUSY)



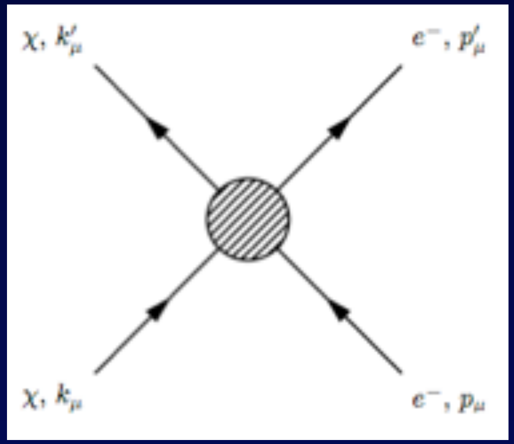
EFT: only SM + DM particle

WIMP models

UV-complete models (SUSY)

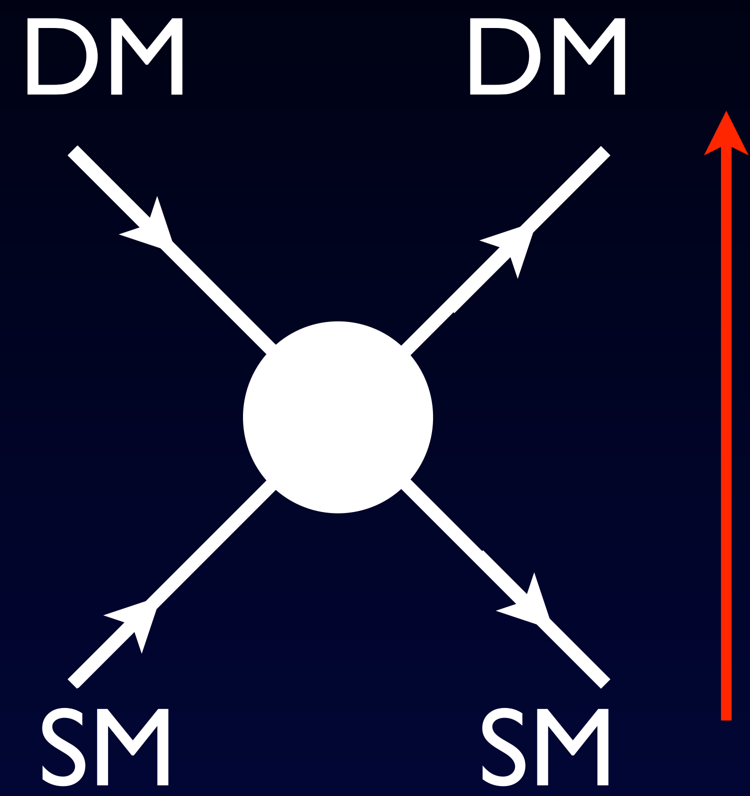


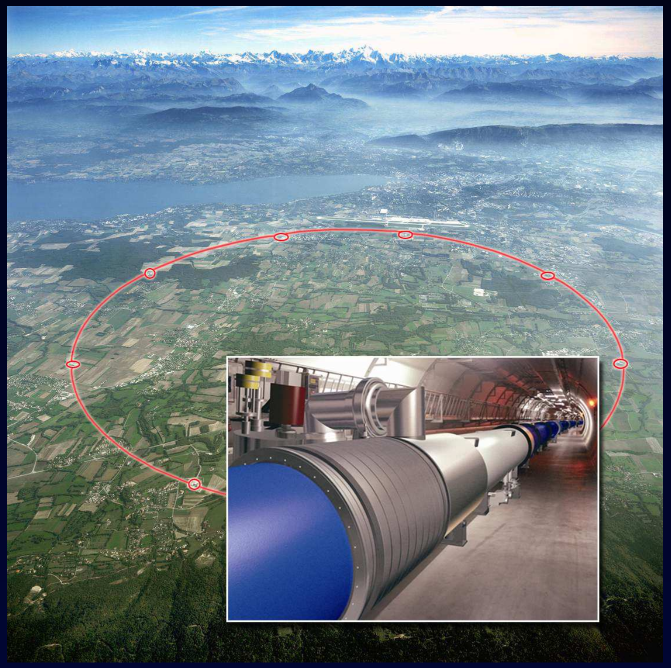
"simplified" models
DM particle + mediator



EFT: only SM + DM particle

DM at LHC





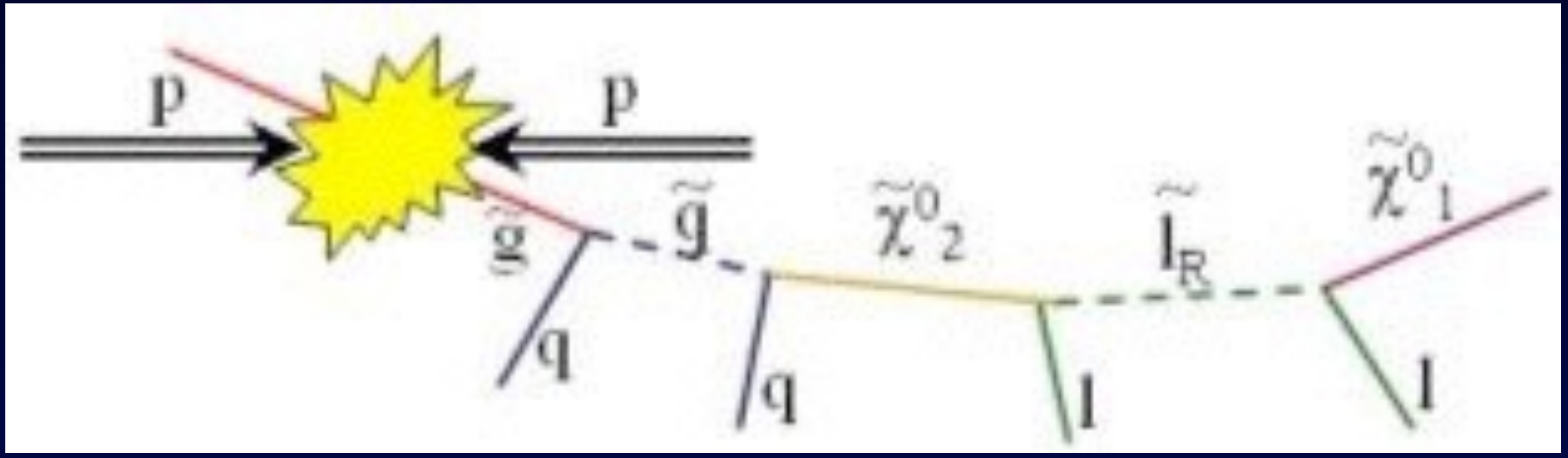
missing energy signature:

- DM particle escapes detector
- invisible particle with life time > 10^{-7} s
- no direct proof that it's DM

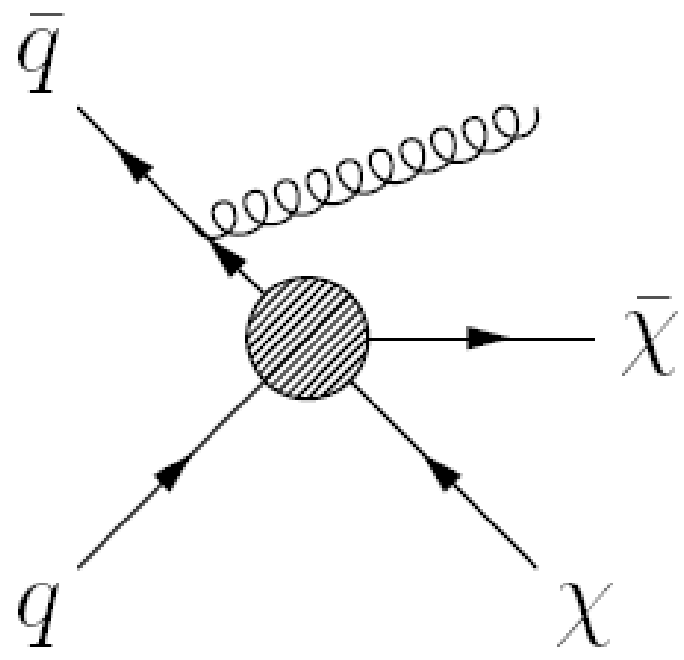
DM at LHC - model dependent searches

look for additional signature of new physics and relate missing energy to DM in a model-dependent way

Ex.: SUSY decay chain



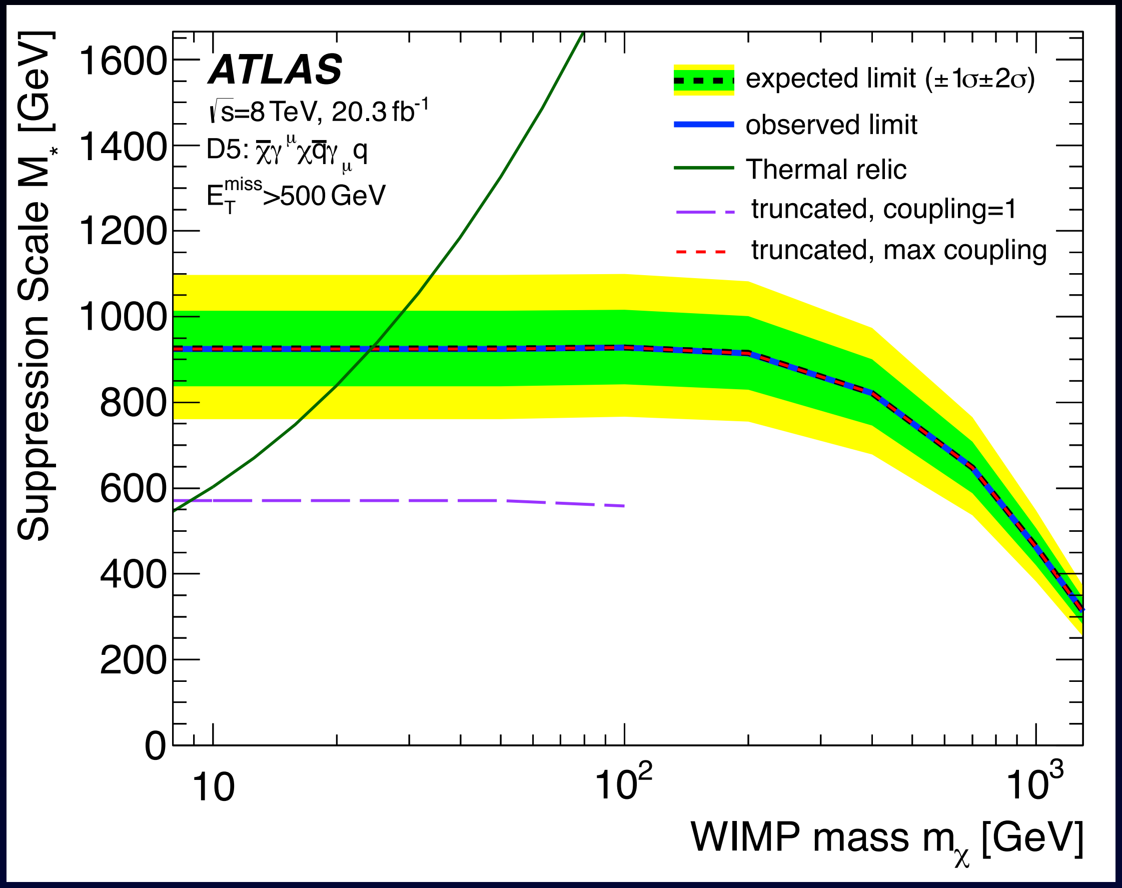
DM at LHC - EFT and mono-j searches

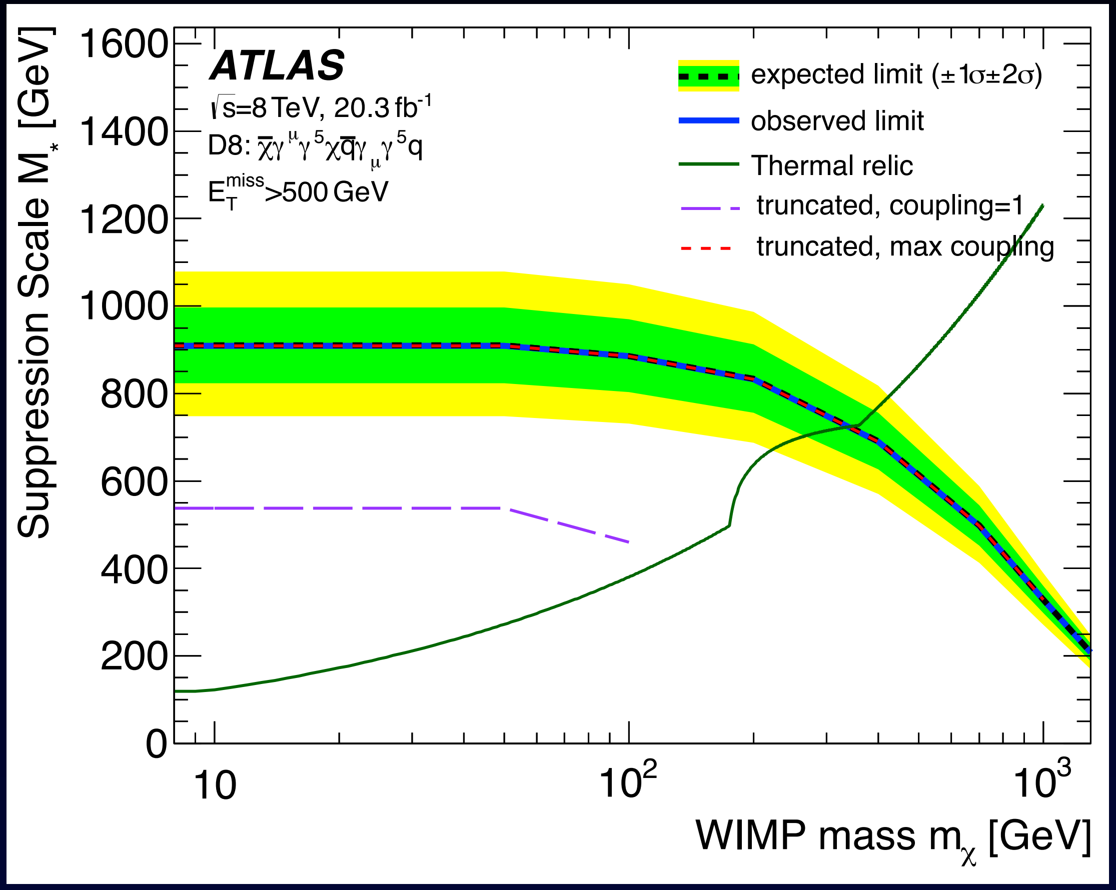


Consider effective vertex of DM with quarks/gluons, e.g.

$$\frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}, \quad \frac{(\bar{\chi}\gamma_5\gamma_\mu\chi)(\bar{q}\gamma_5\gamma^\mu q)}{\Lambda^2}, \quad \frac{(\bar{\chi}\chi)(G_{\mu\nu}G^{\mu\nu})}{\Lambda^3}, \ldots$$

DM at LHC - EFT and mono-j searches

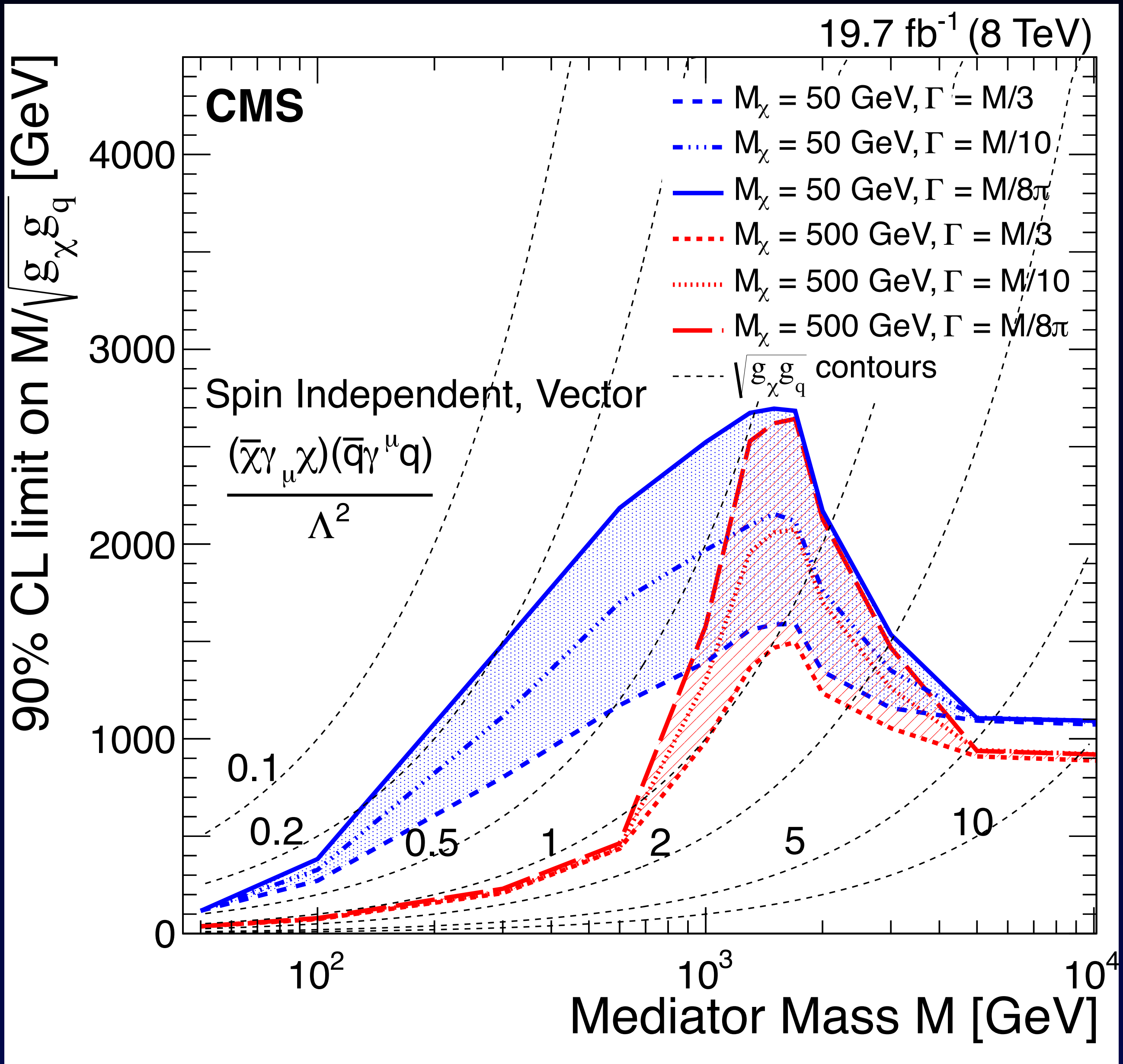




ATLAS, 1502.01518

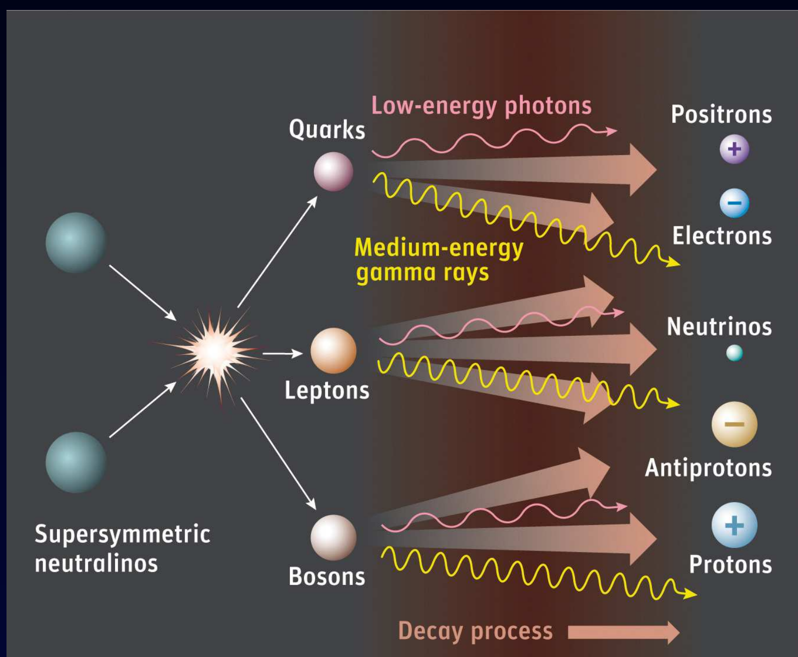
- green curve: correct thermal abundance (assuming only that operator is present)
- EFT description may not be valid at LHC energies
  Buchmuller, Dolan, McCabe, 1308.6799; Busoni et al., 1402.1275, 1405.3101; many more

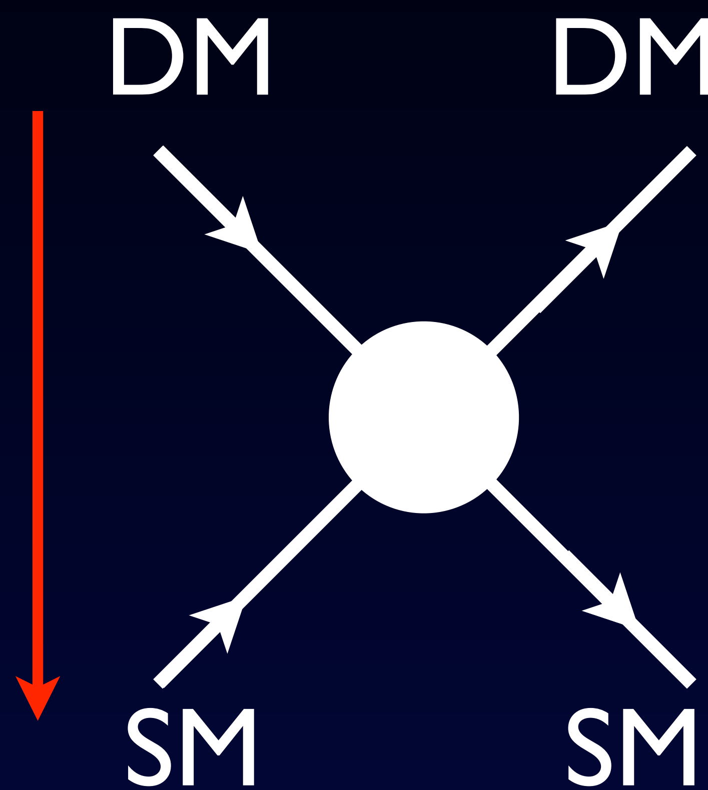
Ex. for simplified model



CMS, 1408.3583

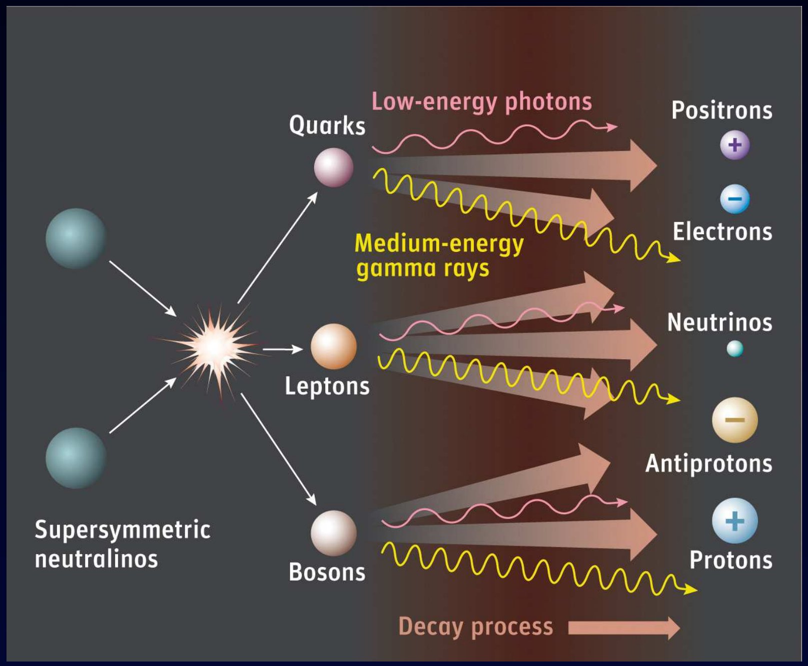
Indirect detection of DM

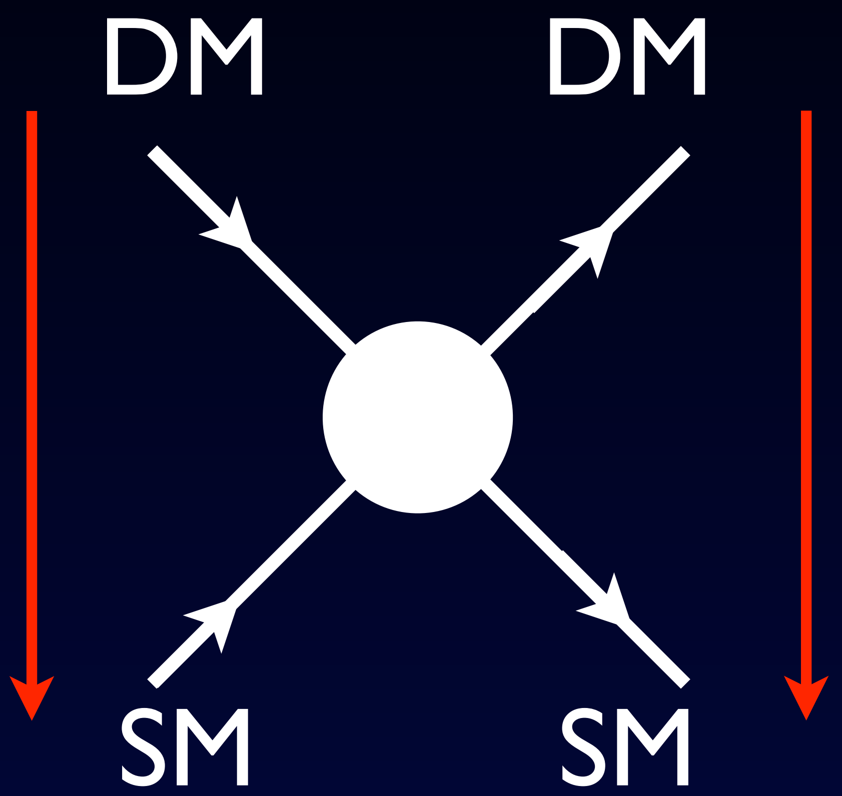




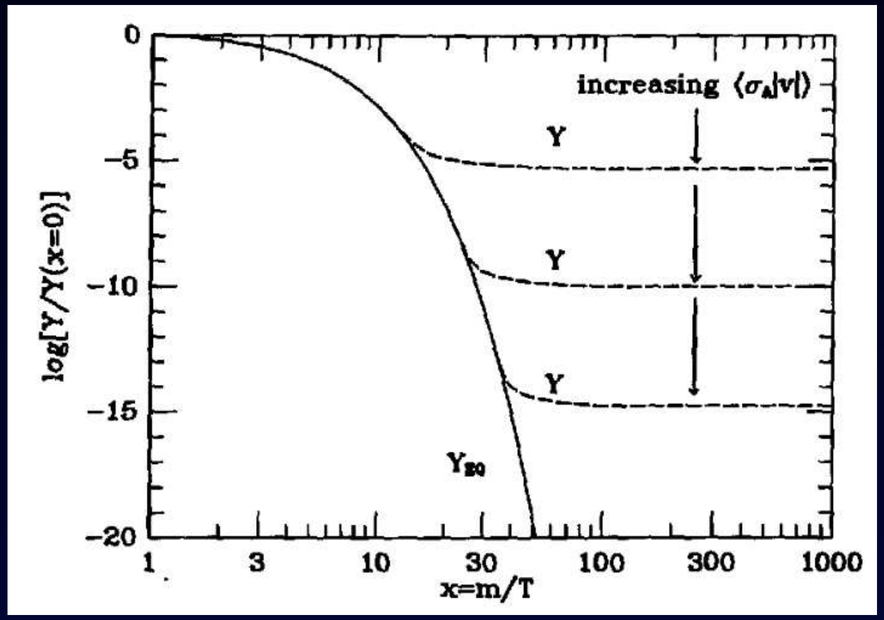
Indirect detection of DM

today





@ freeze-out



Indirect detection of DM

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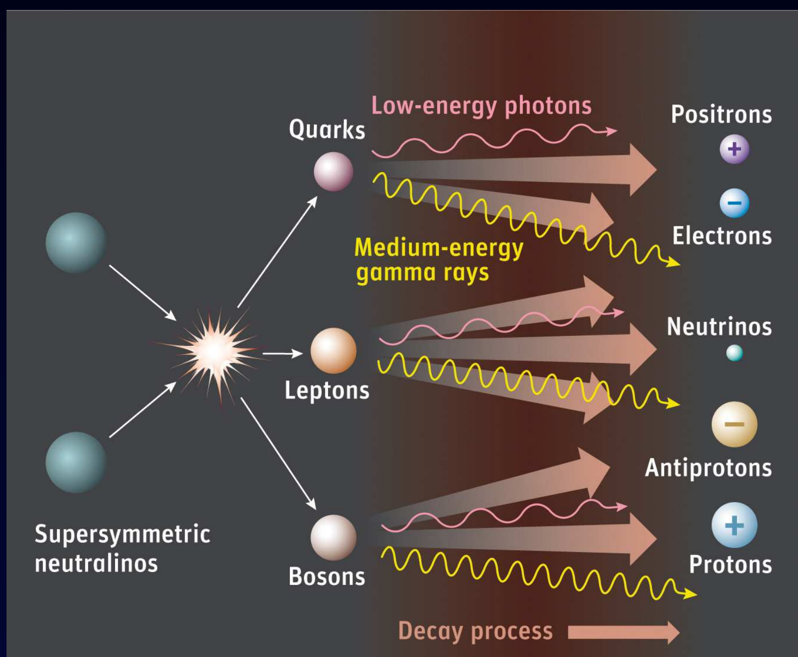
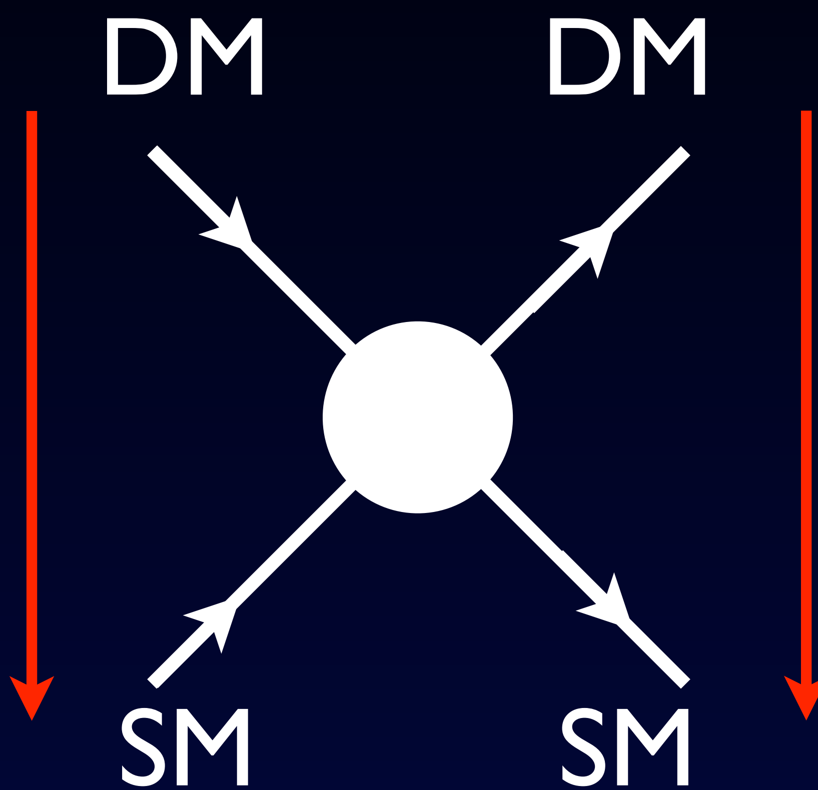
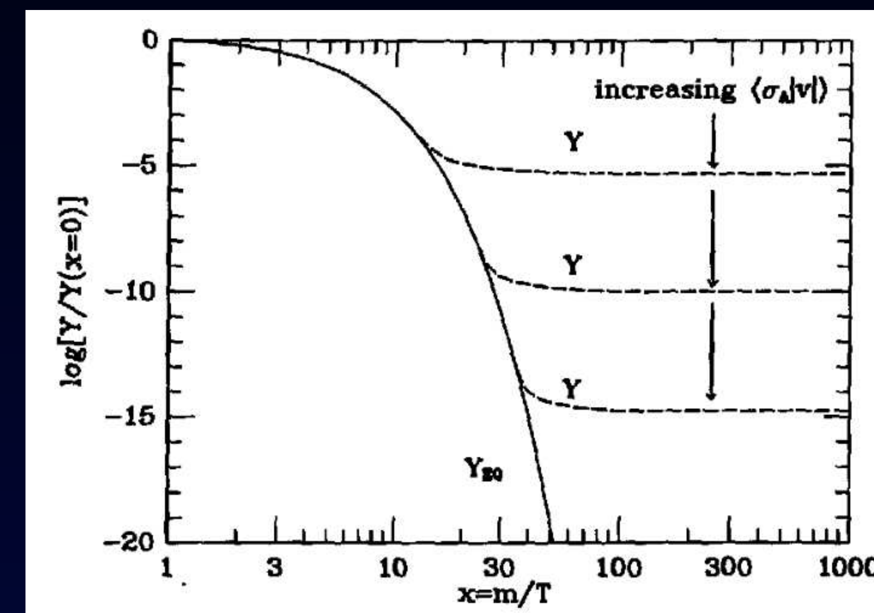




@ freeze-out

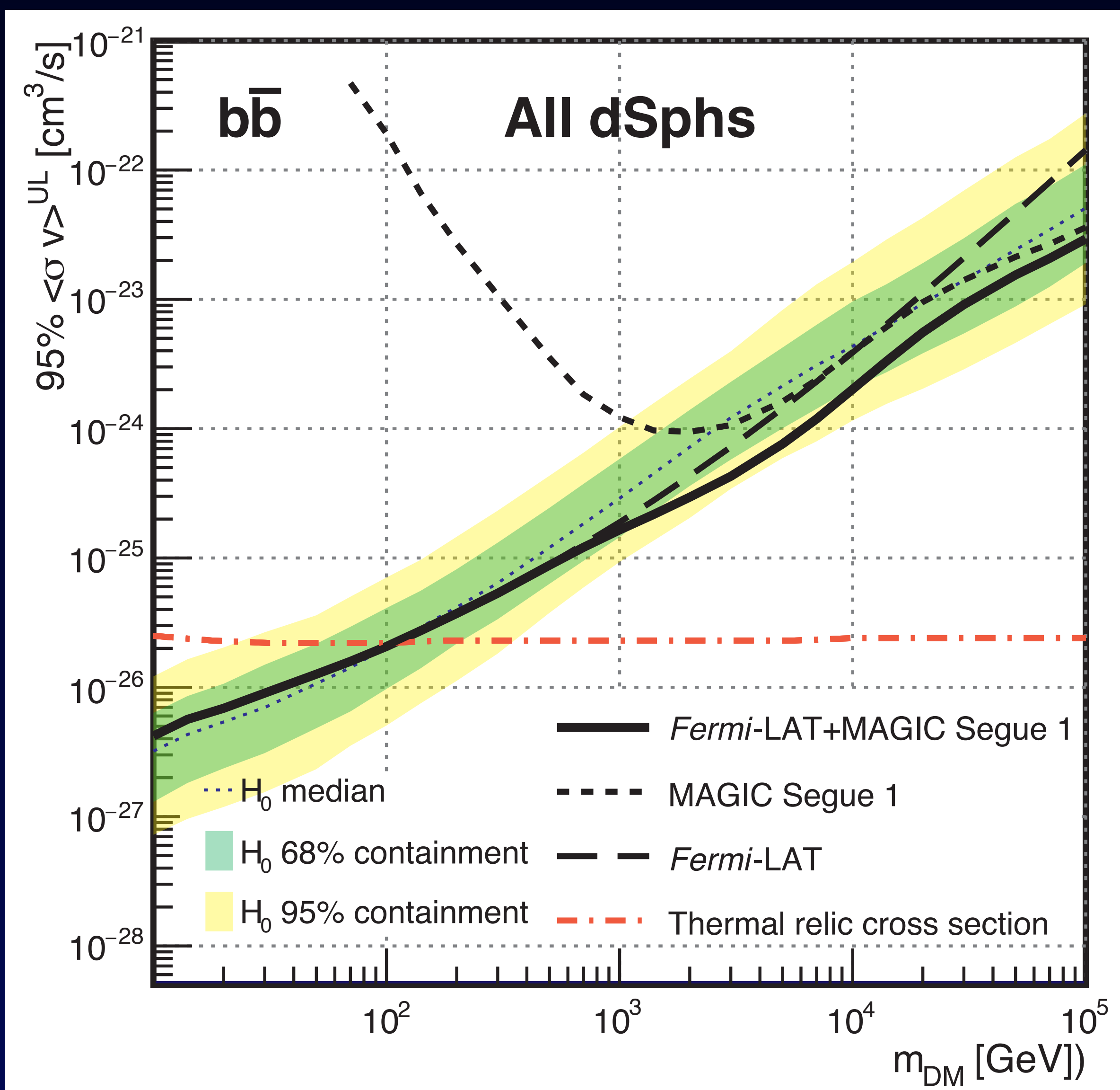


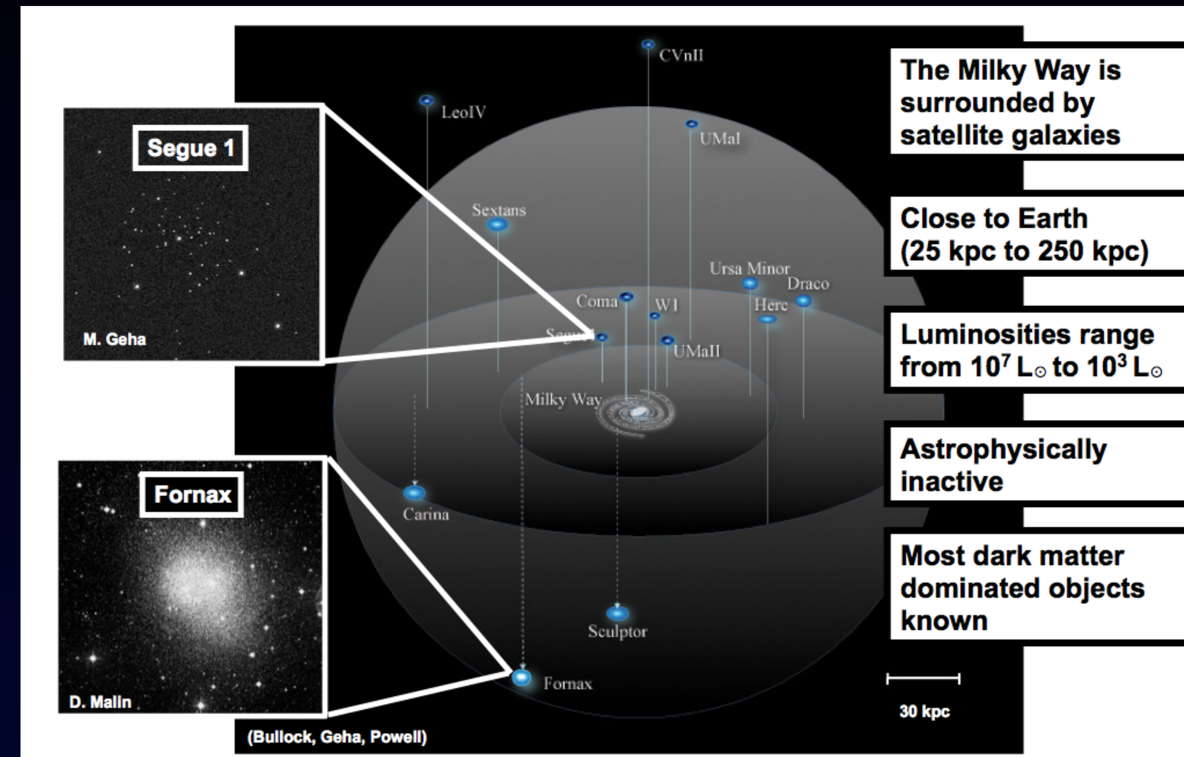
- annihilation cross section today corresponds to the "thermal" one only for s-wave processes (v-independent)
- p-wave annihilations: $\sigma v \sim v^2 \quad \Rightarrow$

  @ 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



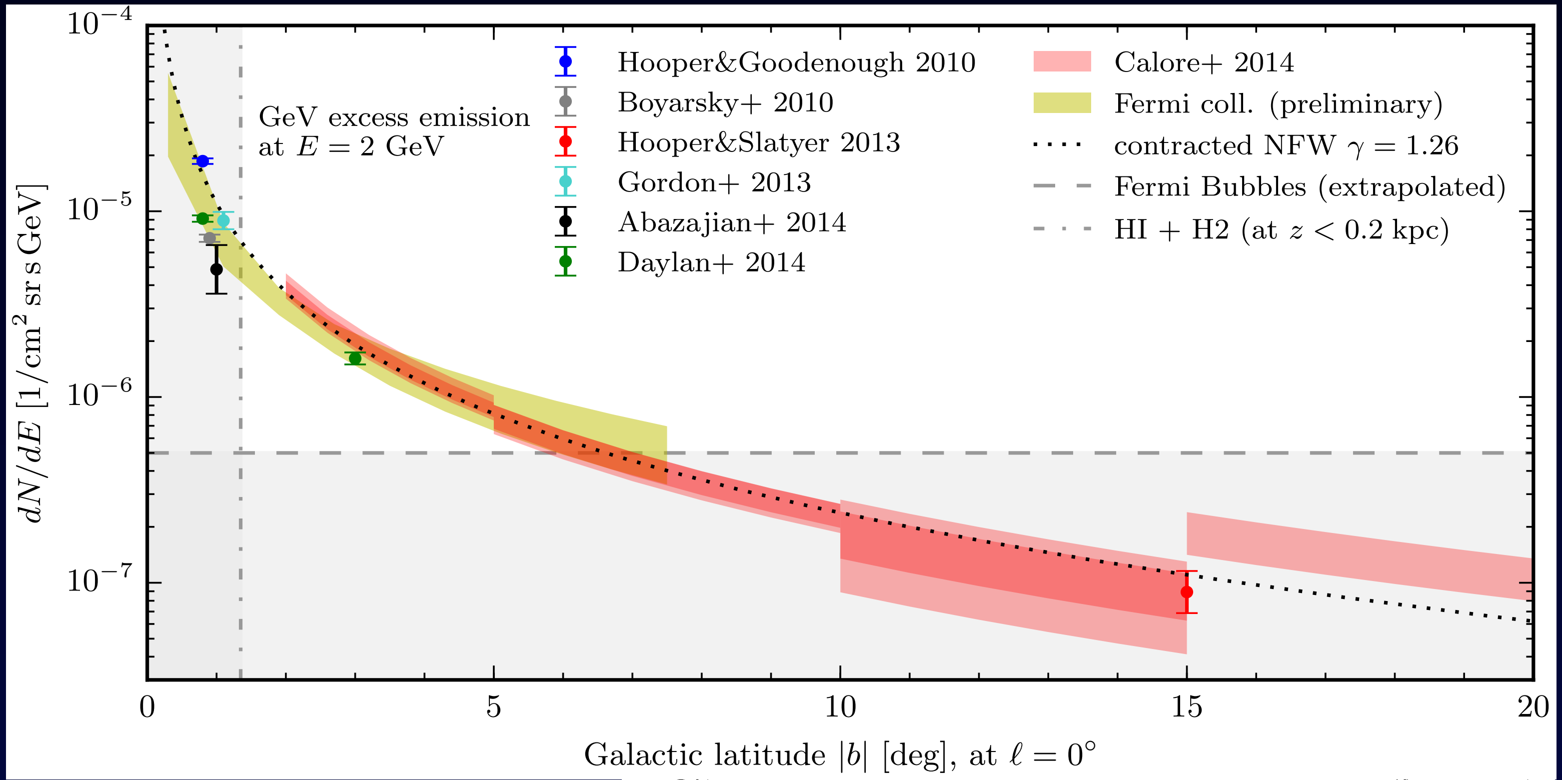


"thermal Xsec" excluded for DM mass < 100 GeV (assuming s-wave annihilation!)

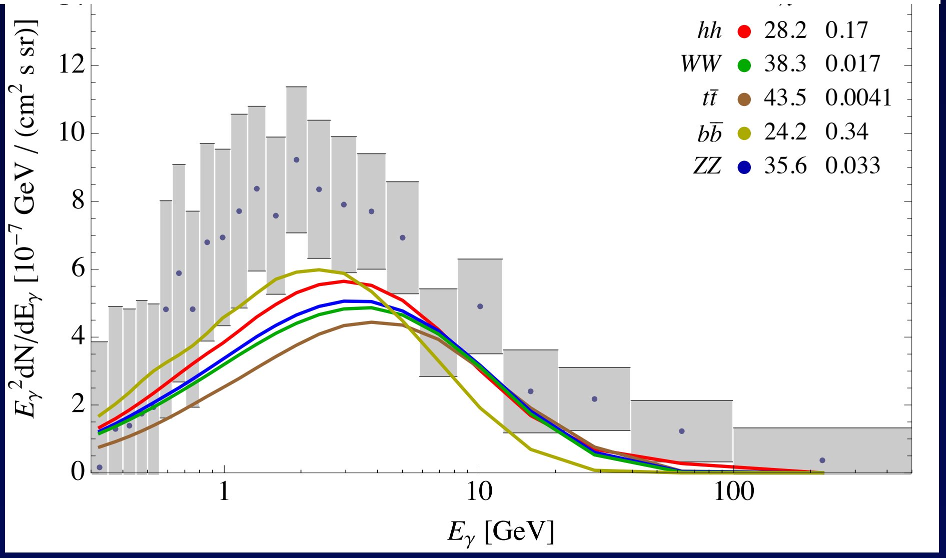
FERMI γ excess from galactic center

Hooper, Goodenough, 2009, 2010; many more

Calore, Cholis, McCabe, Weniger, 1411.4647:

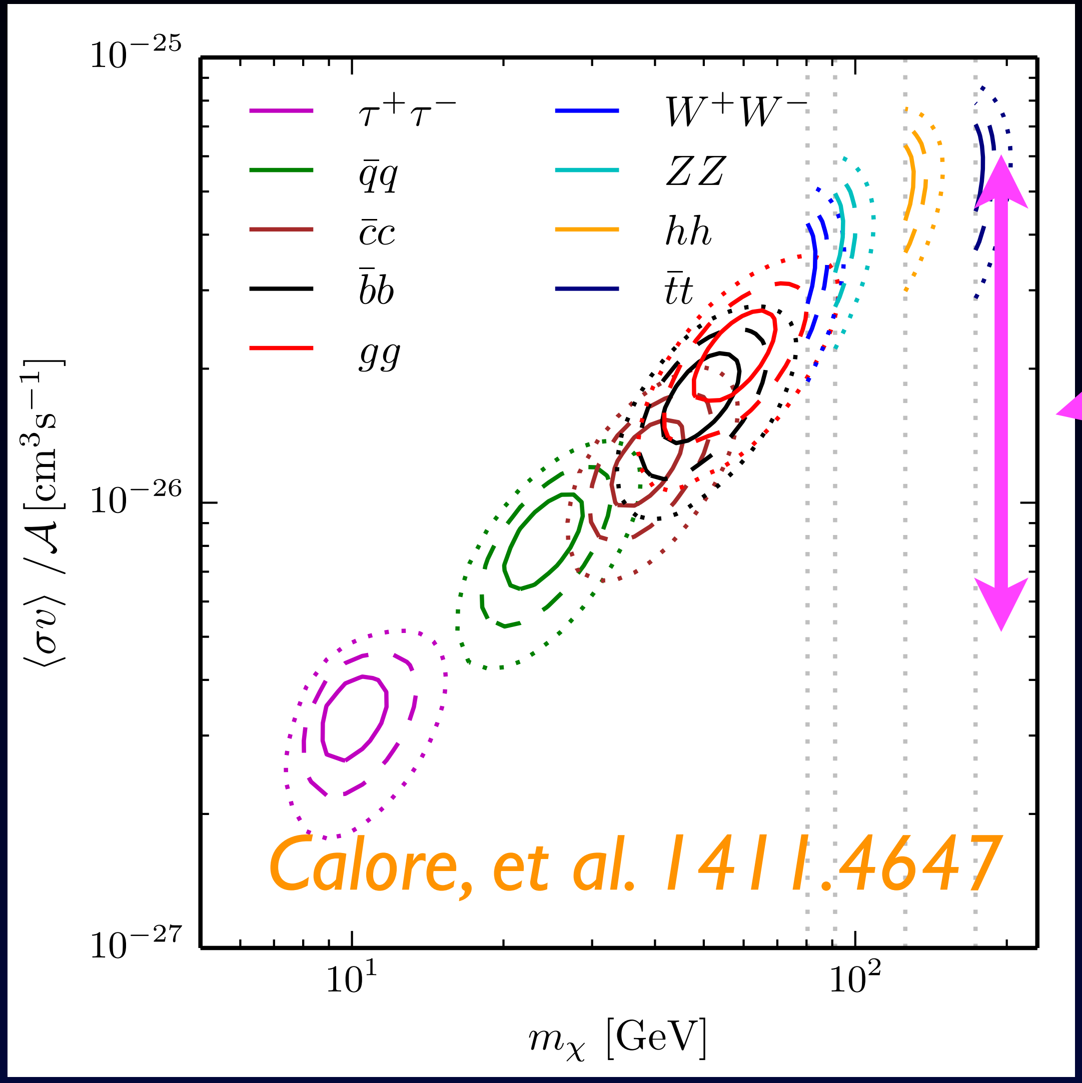


Agrawal, Batell, Fox, Harnik, 1411.2592



- GeV excess robust and highly statistically significant
- with a spectrum, angular distribution, and overall normalization in good agreement with that predicted by simple annihilating dark matter models

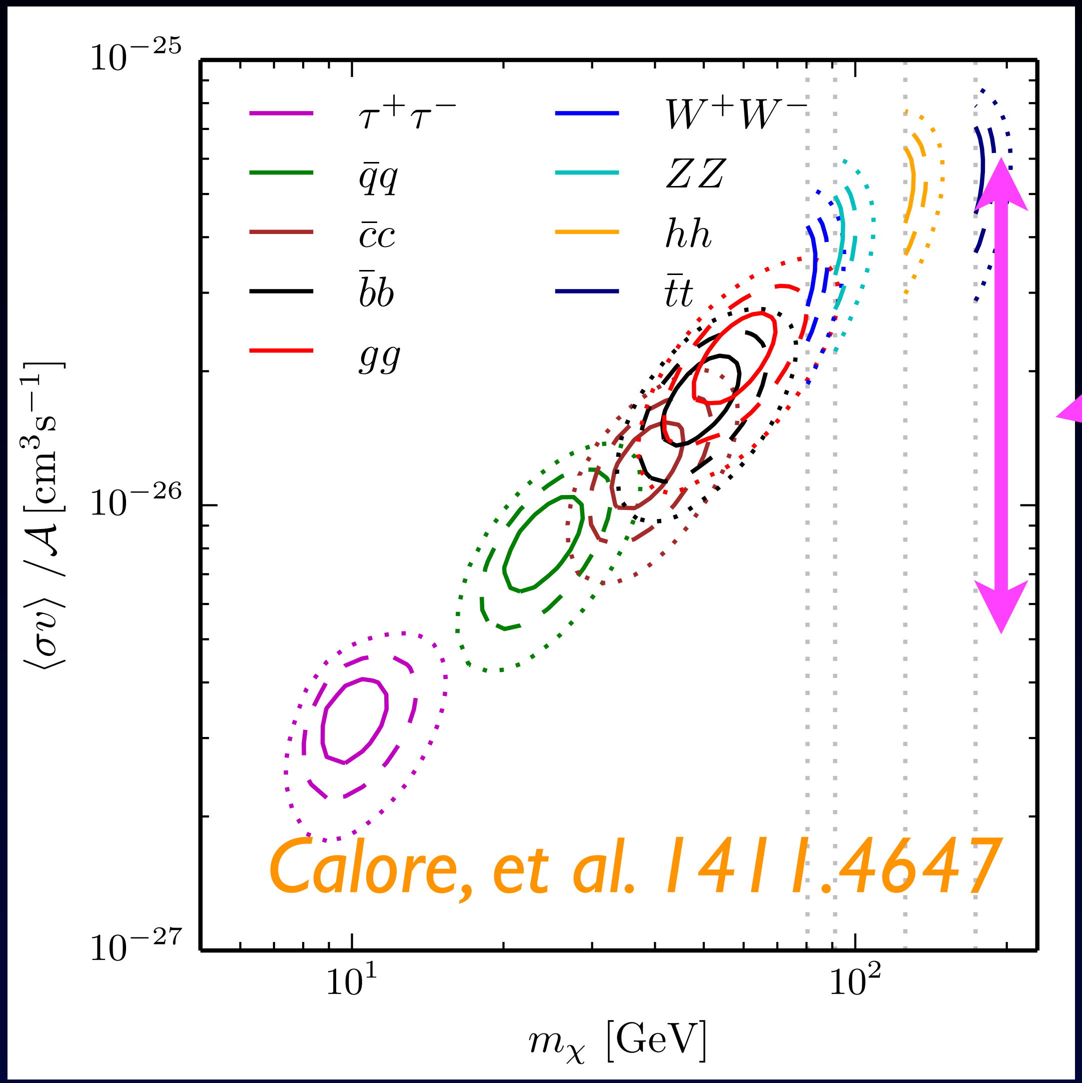
FERMI γ excess from galactic center



range of "thermal" cross sections (incl. astrophys. uncertainty)

consistent with dwarf limits within astrophys. uncertainty

FERMI γ excess from galactic center

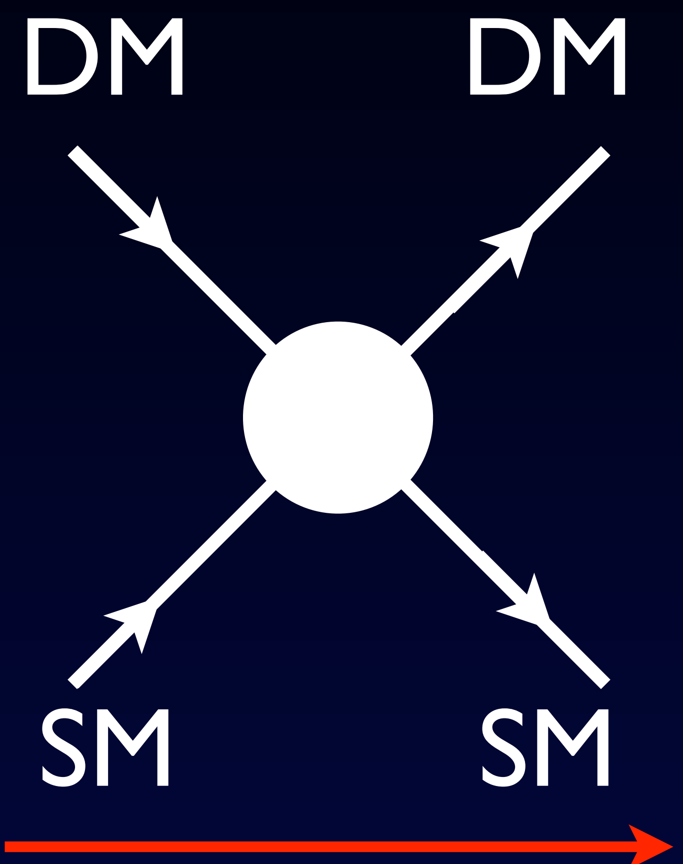


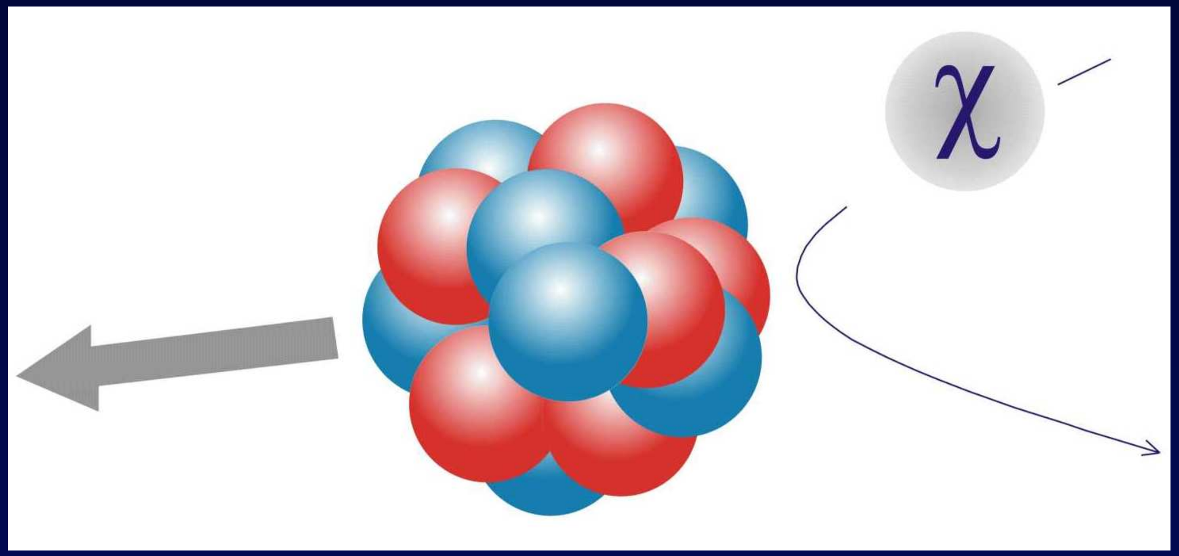
range of "thermal" cross sections (incl. astrophys. uncertainty)

consistent with dwarf limits within astrophys. uncertainty

- Limits on DM interpretation from other channels (antiprotons, radio waves, positrons) *Bringmann, Vollmann, Weniger, 1406.6027*
- non-DM explanations, e.g. milli-second pulsars, non-stationary state of cosmic rays in GC (e.g., burst event 10^6 yrs ago) *Petrovic, Serpico, Zaharijas, 2014*

DM direct detection





Direct detection - signature

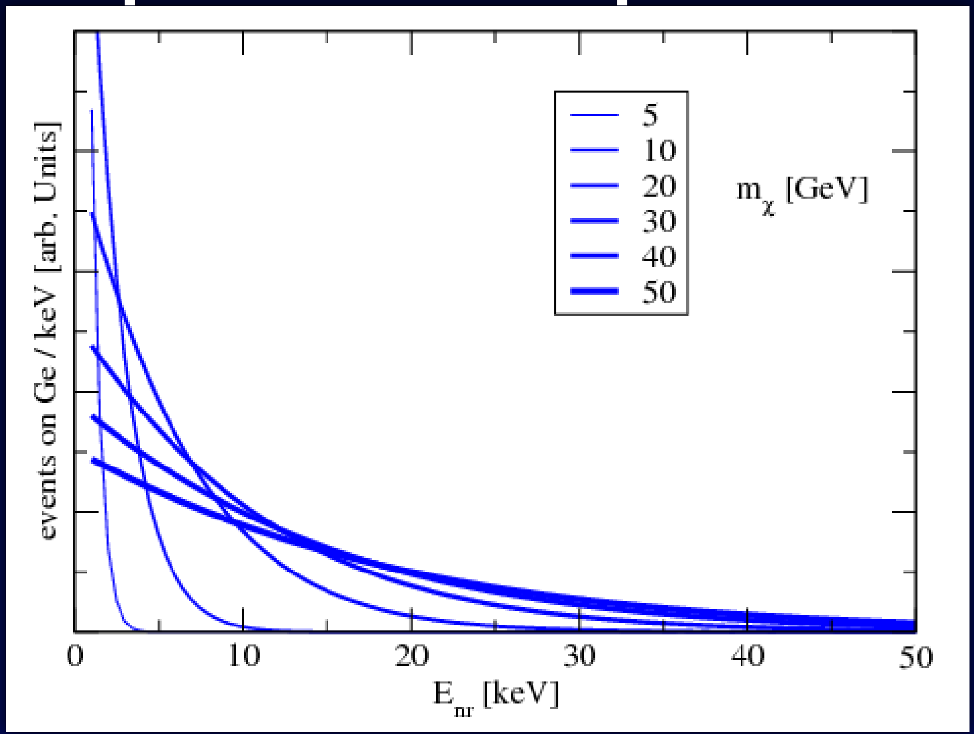
talk by N. Foerster

events / keV :

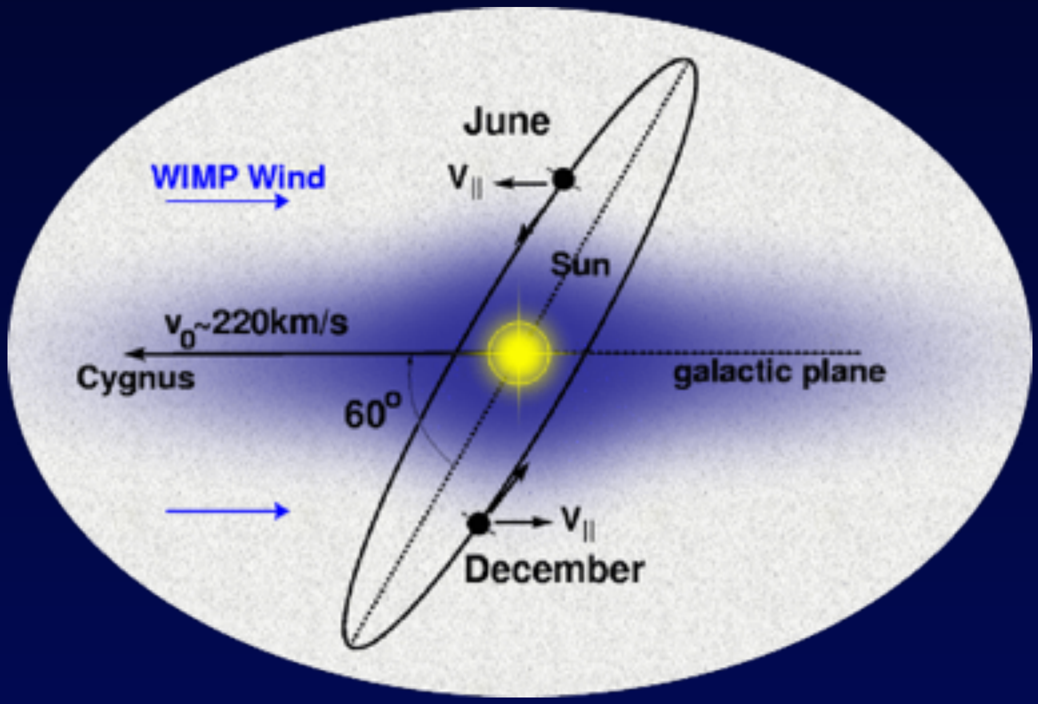
$$\frac{dN}{dE_R} \propto \frac{\rho_{\rm DM}}{m_{\rm DM}} \int_{v>v_{\rm min}} d^3v \frac{d\sigma}{dE_R} v f_\oplus(\vec{v}, t)$$

$$f_\oplus(\vec{v}, t) = f(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t))$$

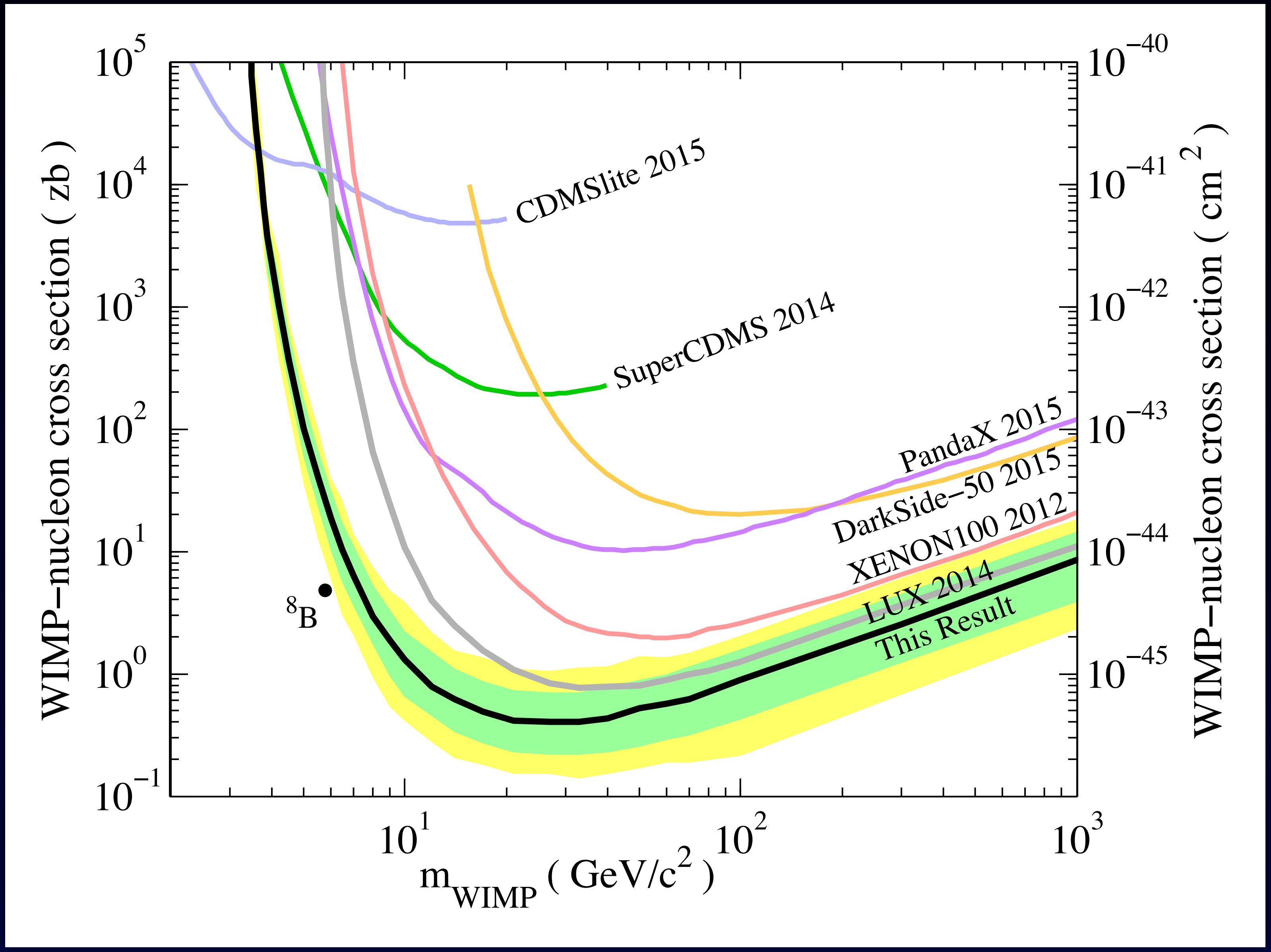
exponential spectrum



annual modulation

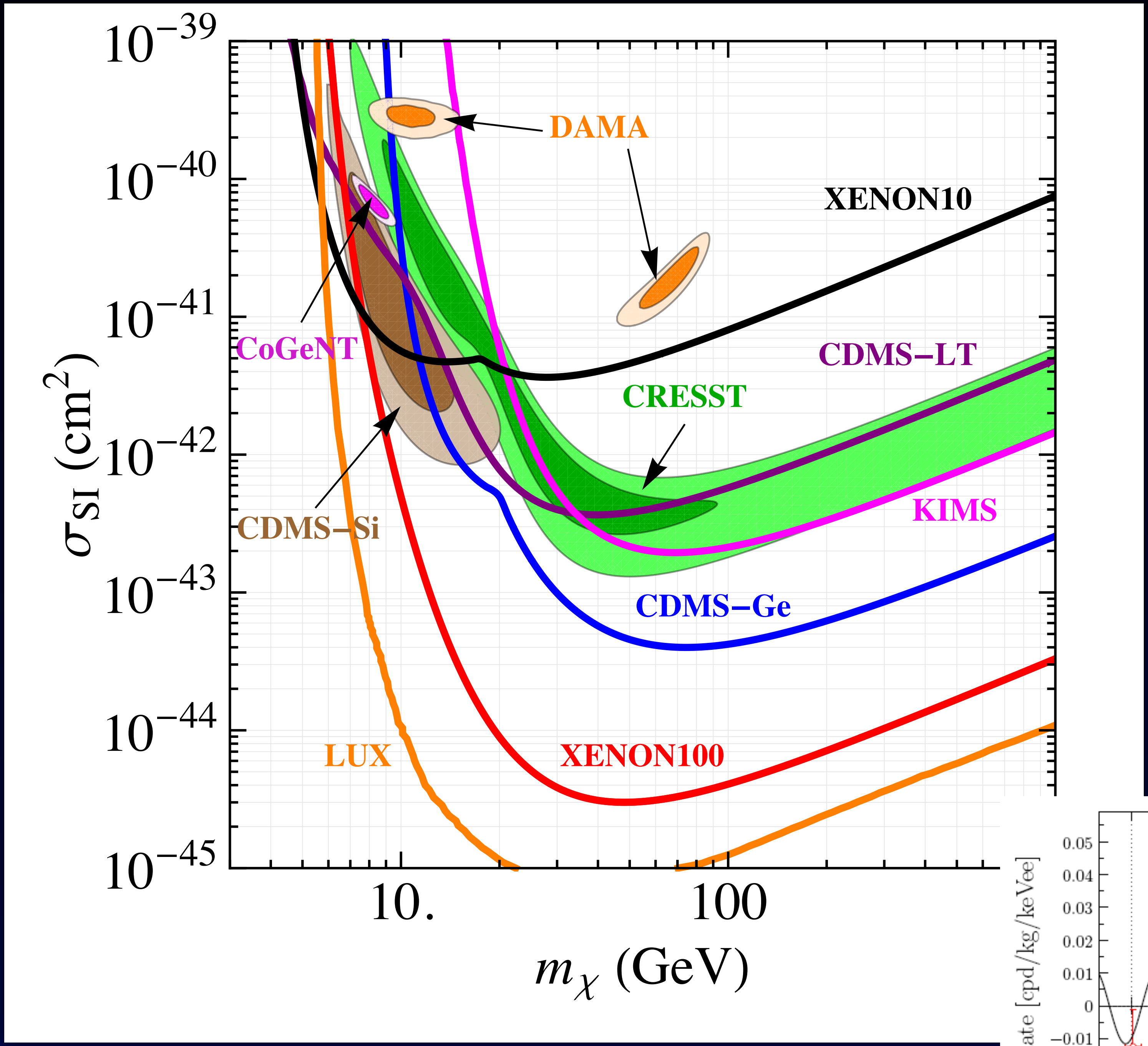


Direct detection - status



LUX, 1512.03506

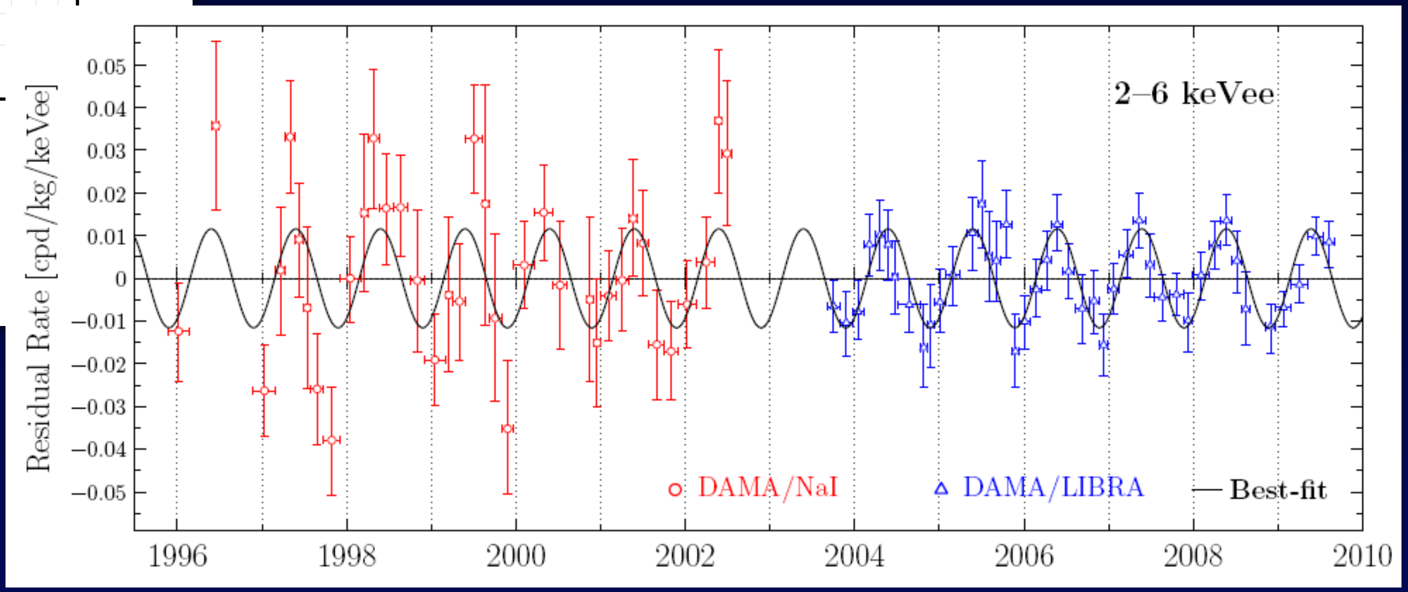
Direct detection - status



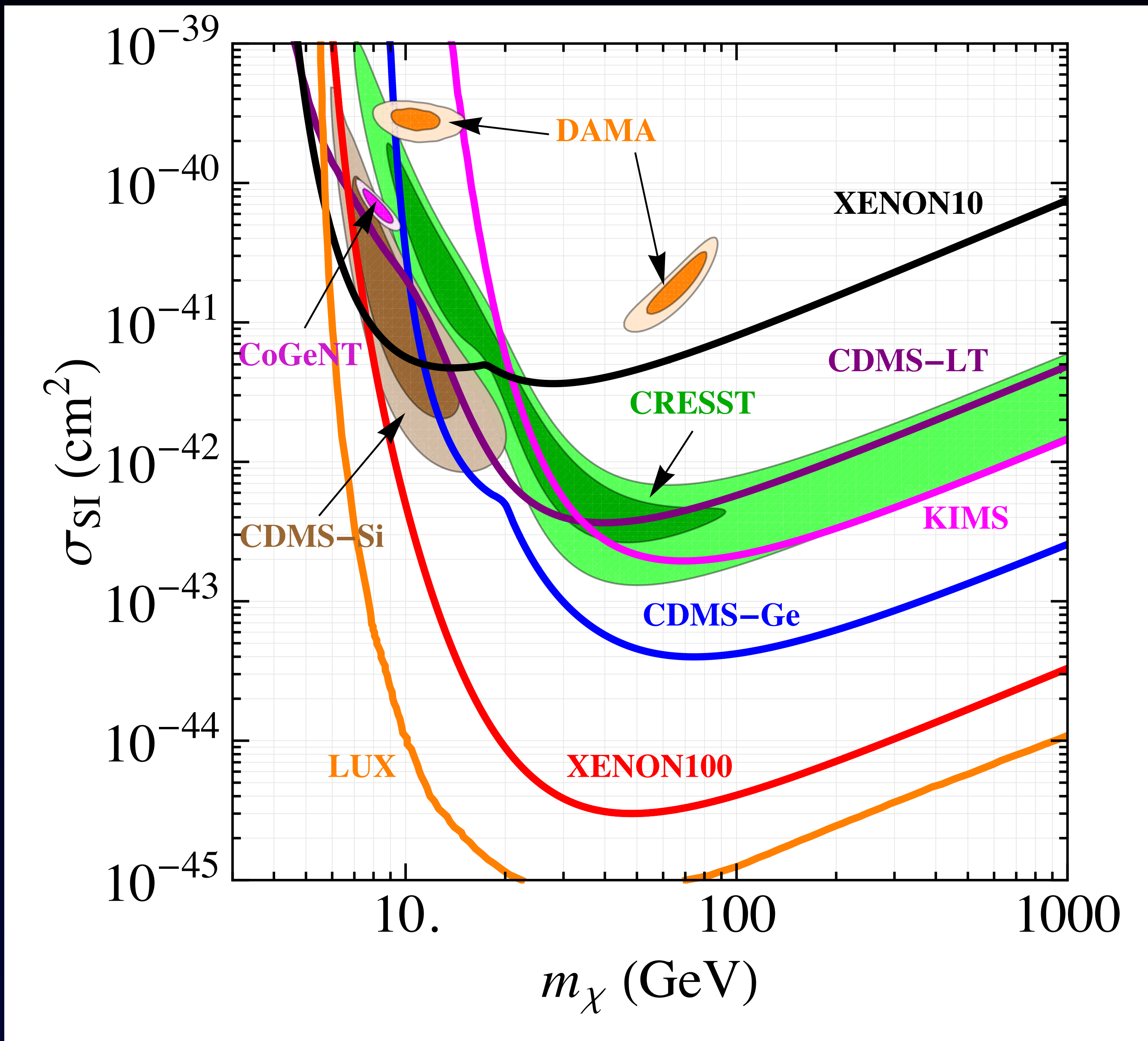
Bozorgnia, Catena, Schwetz, 2013

- DAMA: highly significant signal for annual modulation
- CDMS-Si: 3 events, P=0.19% LH-test

DAMA/LIBRA



Direct detection - status



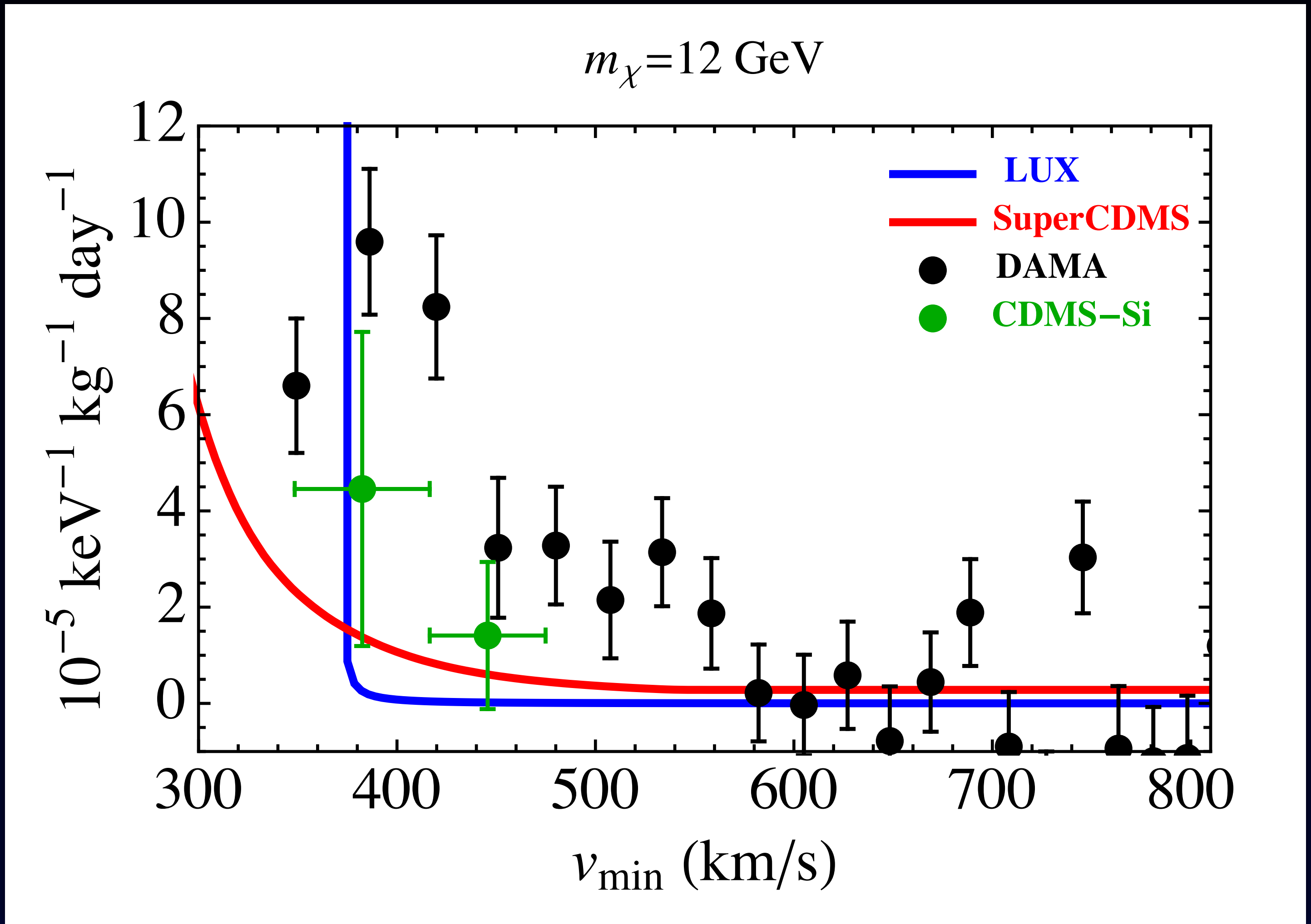
Bozorgnia, Catena, Schwetz, 2013

- DAMA: highly significant signal for annual modulation
- CDMS-Si: 3 events, P=0.19% LH-test

in tension with limits

dependent on
- particle physics
- astrophysics

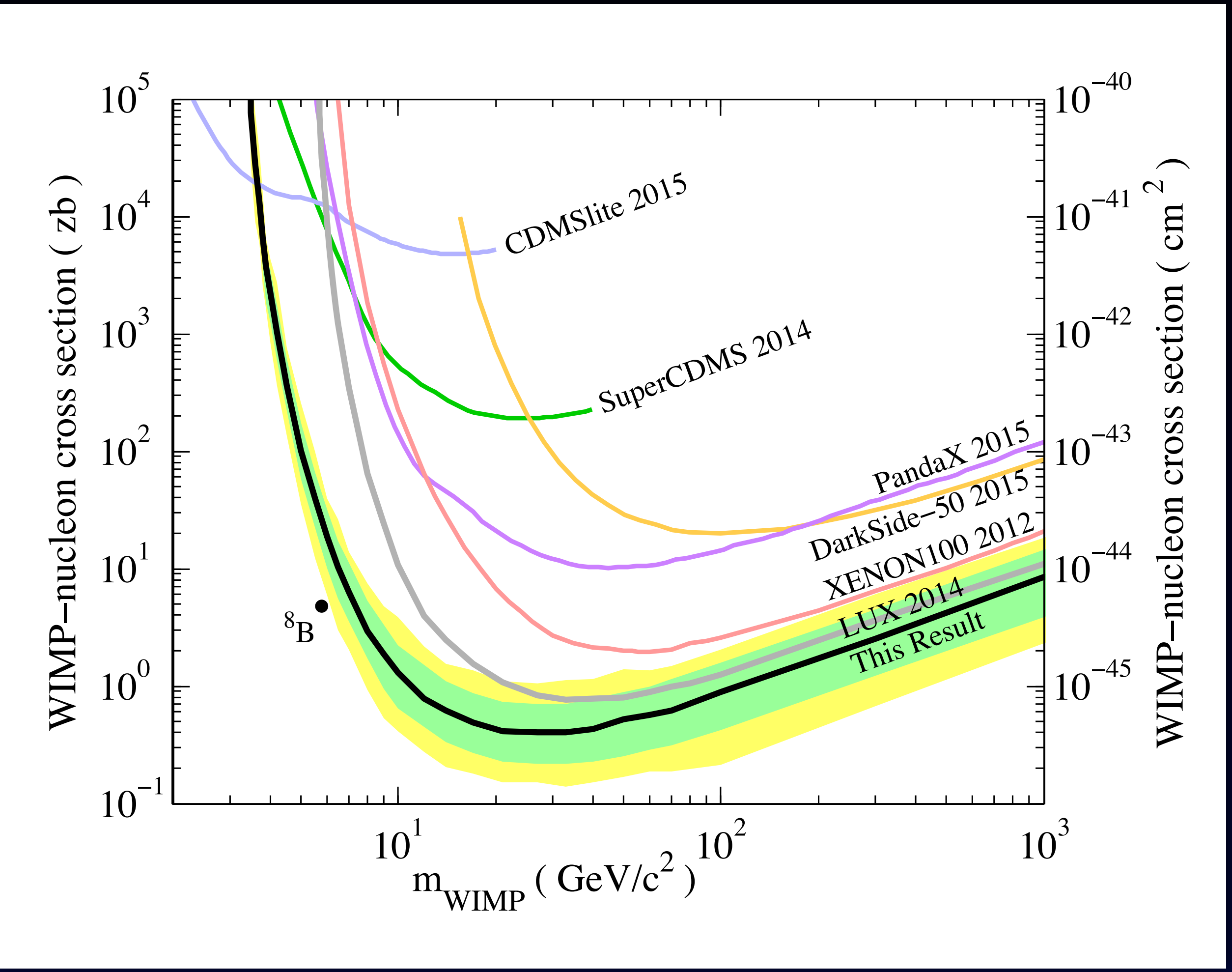
DM-halo independent comparison of experiments



Bozorgnia, Schwetz, 1410.6160

s. also delNobil, Feldstein, Fox, Frandsen, Gelmini, Gondolo, Kahlhöfer, Harnik, McCabe, Sarkar, ...

Direct detection and the WIMP hypothesis



- testing cross sections $\sim 10^{-45}$ cm^2
- parameter region motivated by WIMP argument (thermal freeze-out) model dependent!

$\sigma_{scatt} < 10^{-45}$ cm^2 $\overset{?}{\leftrightarrow}$ $\sigma_{annih.} \sim 10^{-36}$ cm^2

Direct detection and the WIMP hypothesis

Ex. 1: Higgs-portal with fermionic DM χ

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

Direct detection and the WIMP hypothesis

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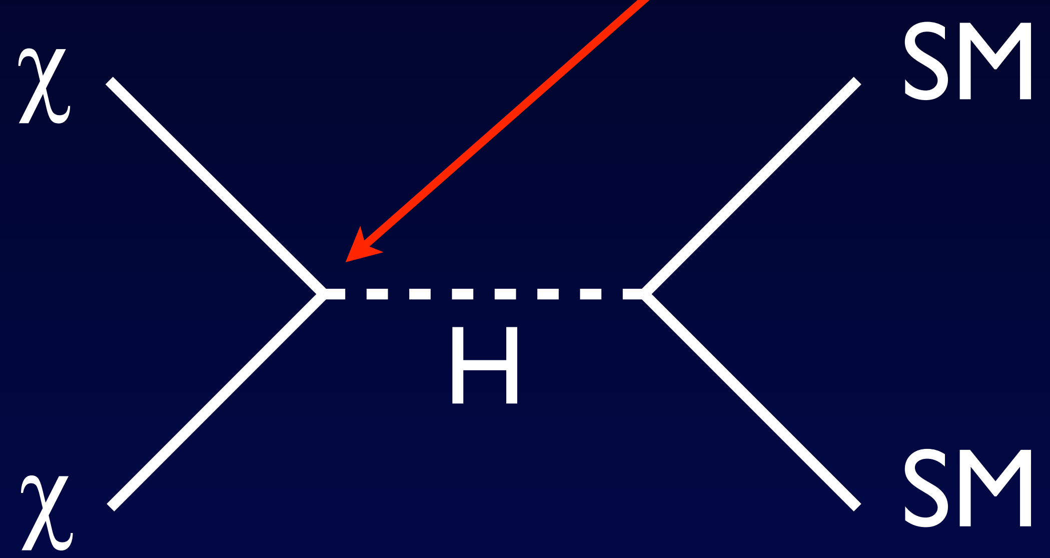
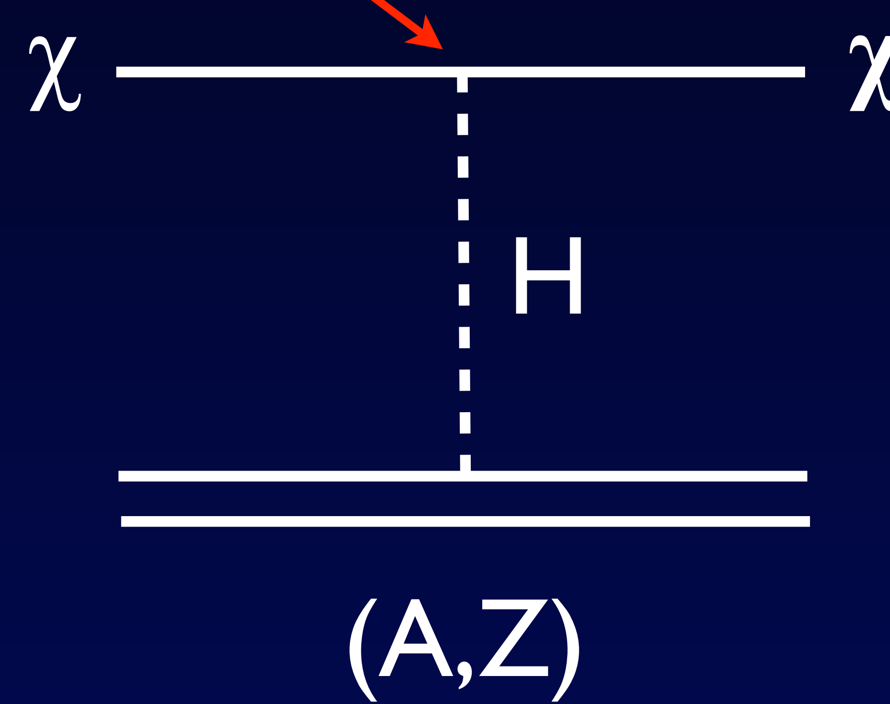
$$\frac{1}{\Lambda_1}(\bar{\chi}\chi)(H^\dagger H)$$

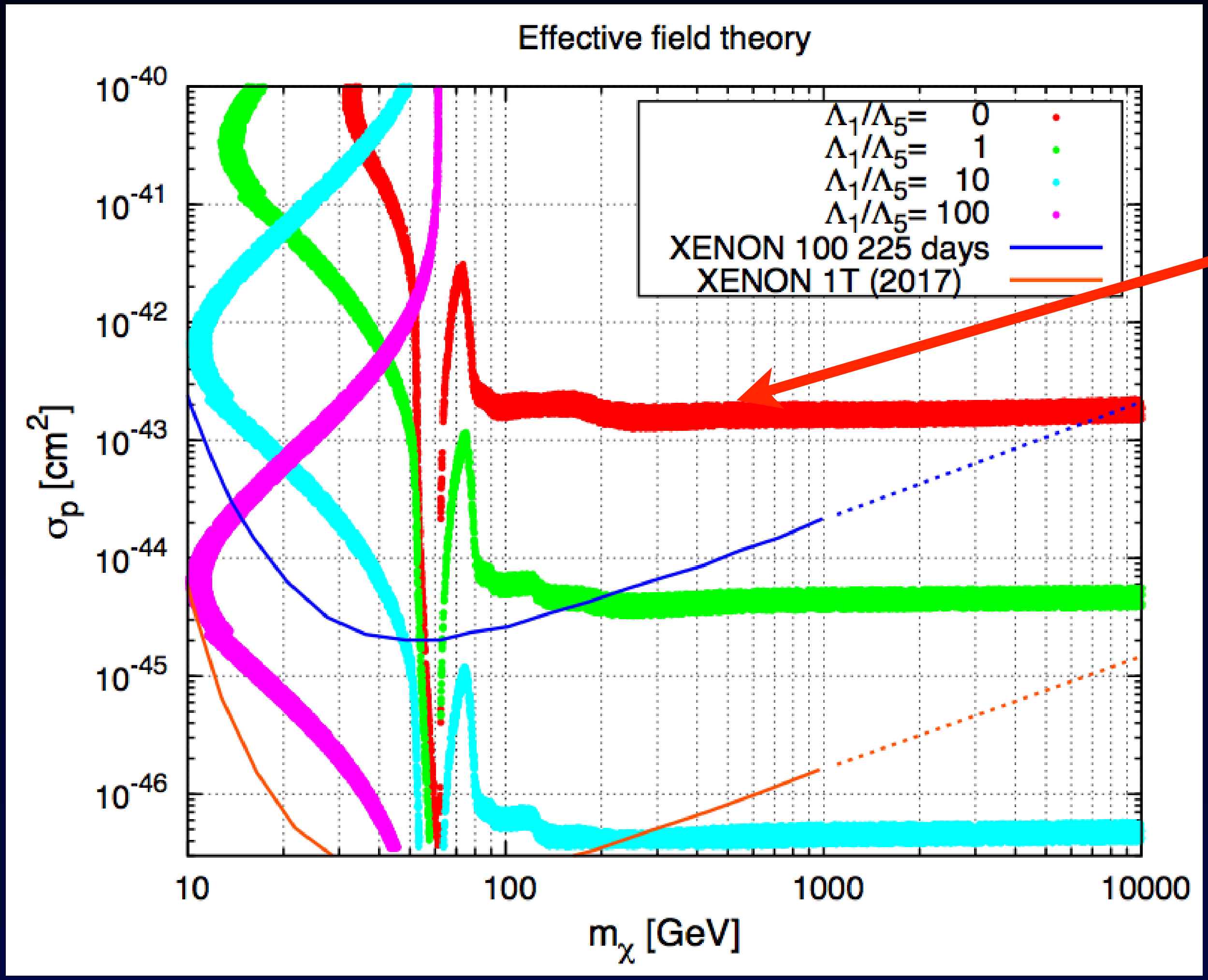
annihilation:



scattering:



Higgs portal

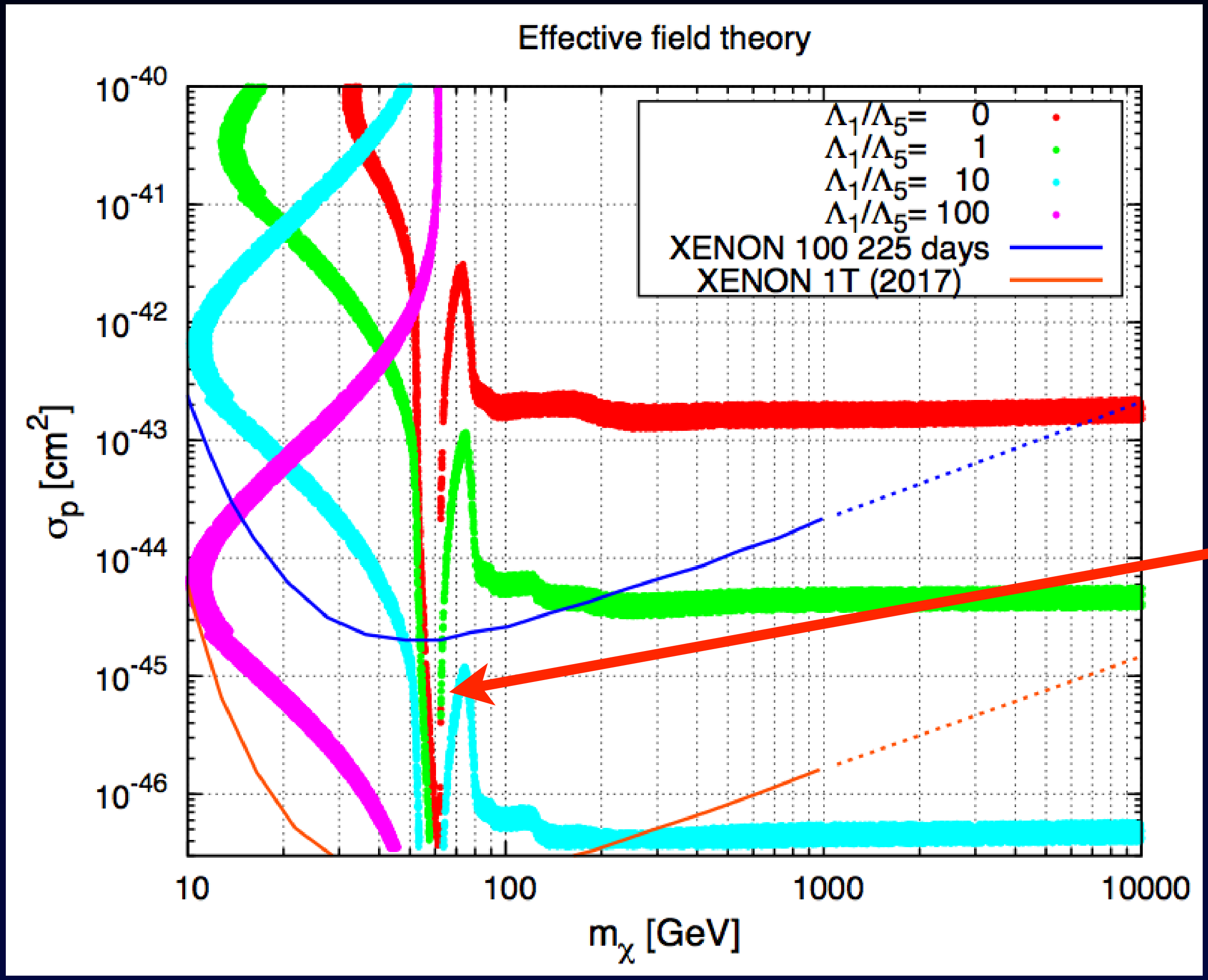


- excluded by XENON, LUX

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

Lopez-Honorez, TS, Zupan, 12

Higgs portal



Lopez-Honorez, TS, Zupan, 12

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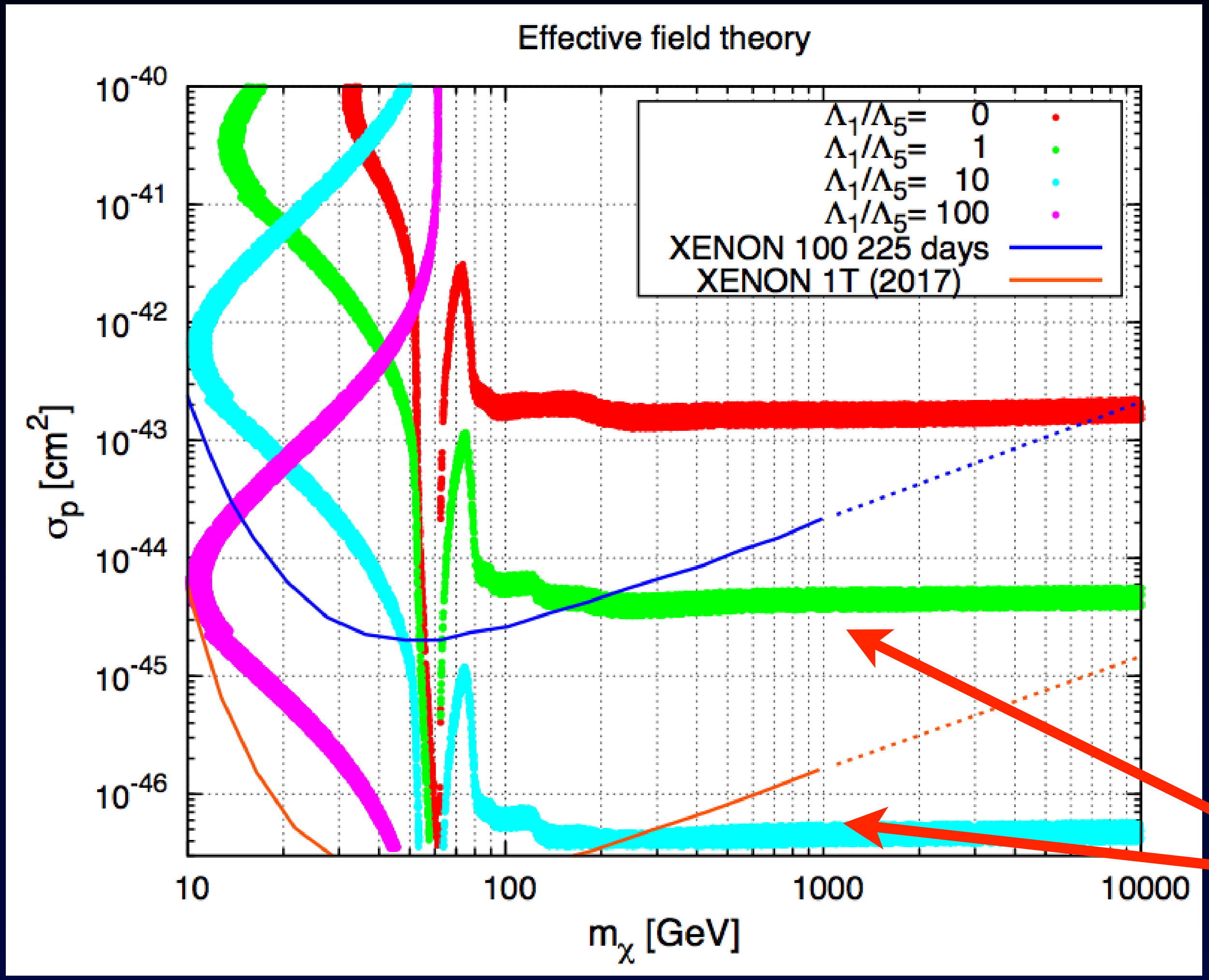
$$\frac{1}{\Lambda_1}(\bar{\chi}\chi)(H^\dagger H)$$

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

Higgs portal



Lopez-Honorez, TS, Zupan, 12

- excluded by XENON, LUX

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

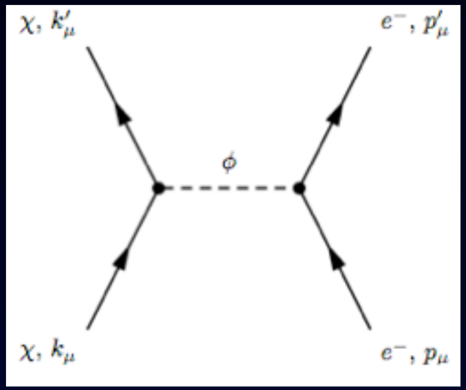
- s-channel resonance at $m_\chi \approx m_H/2$

- pseudo-scalar Higgs-Portal

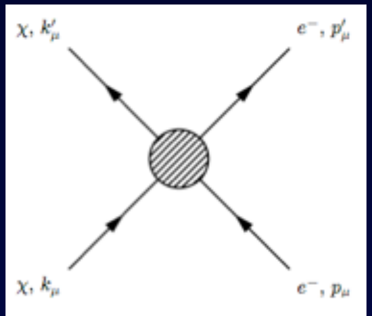
$$\frac{1}{\Lambda_5}(\overline{\chi}\gamma_5\chi)(H^\dagger H)$$

Joint analysis only possible within a specific model

UV-complete models (SUSY)



"simplified" models
DM particle + mediator



EFT: only SM + DM particle

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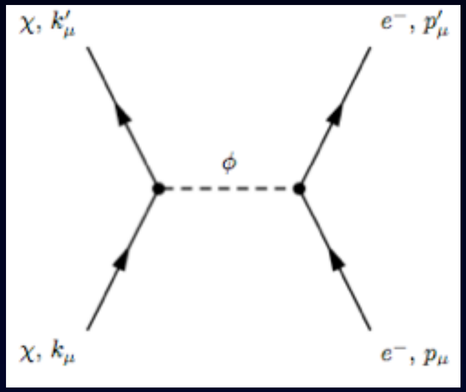
UV-complete models (SUSY)

MSSM industry



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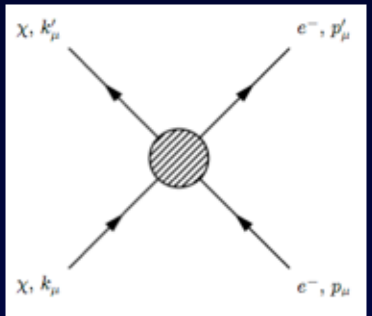

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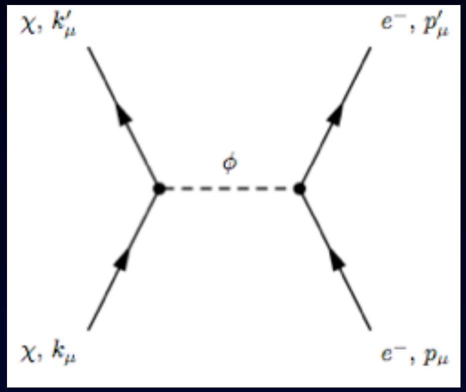

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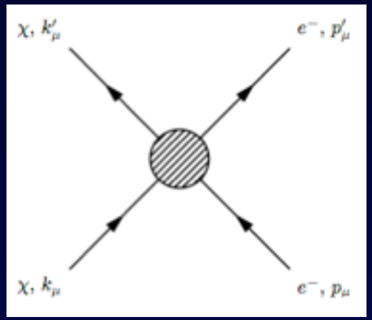

EFT: only SM + DM particle

conceptual problems (LHC, annih., loops)

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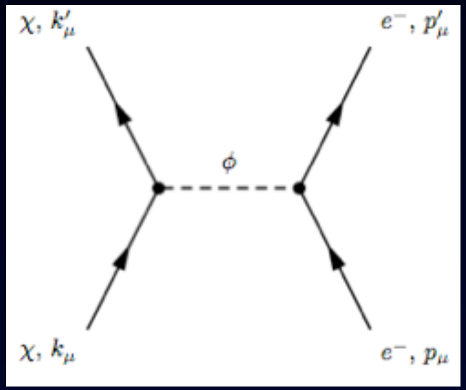
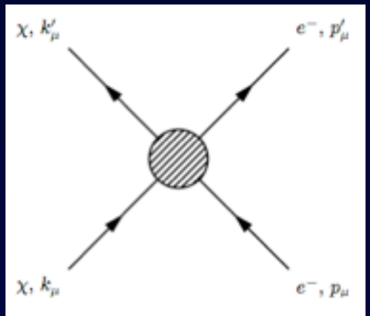


"simplified" models
DM particle + mediator

(potentially) well defined



EFT: only SM + DM particle

conceptual problems
(LHC, annih., loops)

Example for a consistent „simplified“ model

Kahlhoefer, Schmidt-Hoberg, Schwetz, Vogl, 1510.02110

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

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

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Higgs mixing and kinetic mixing open new portals to SM

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

Example for a consistent „simplified“ model

Kahlhoefer, Schmidt-Hoberg, Schwetz, Vogl, 1510.02110

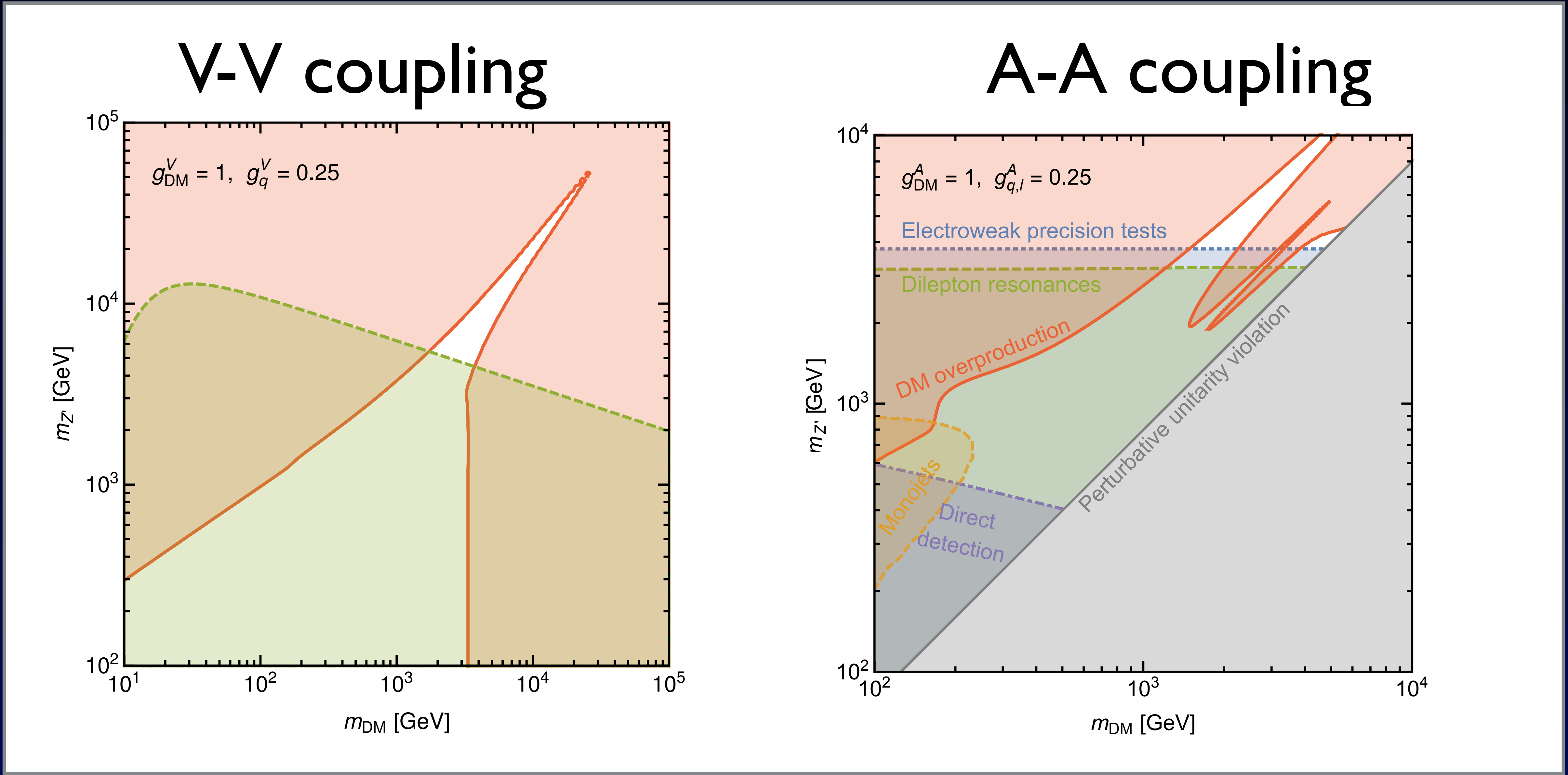
SM +

- U(1) gauge symmetry (Z')
- Fermionic DM particle
- dark Higgs S breaking the U(1)

- Z' (vector) and S (scalar) mediator particles
- unitarity provides constraint on parameter space
- gauge invariance implies certain constraints on couplings (e.g., to leptons → dilepton resonances)
- kinetic and mass mixing of the Z-Z' → additional interaction channels + constraints from EWPT

Z' mediated interaction

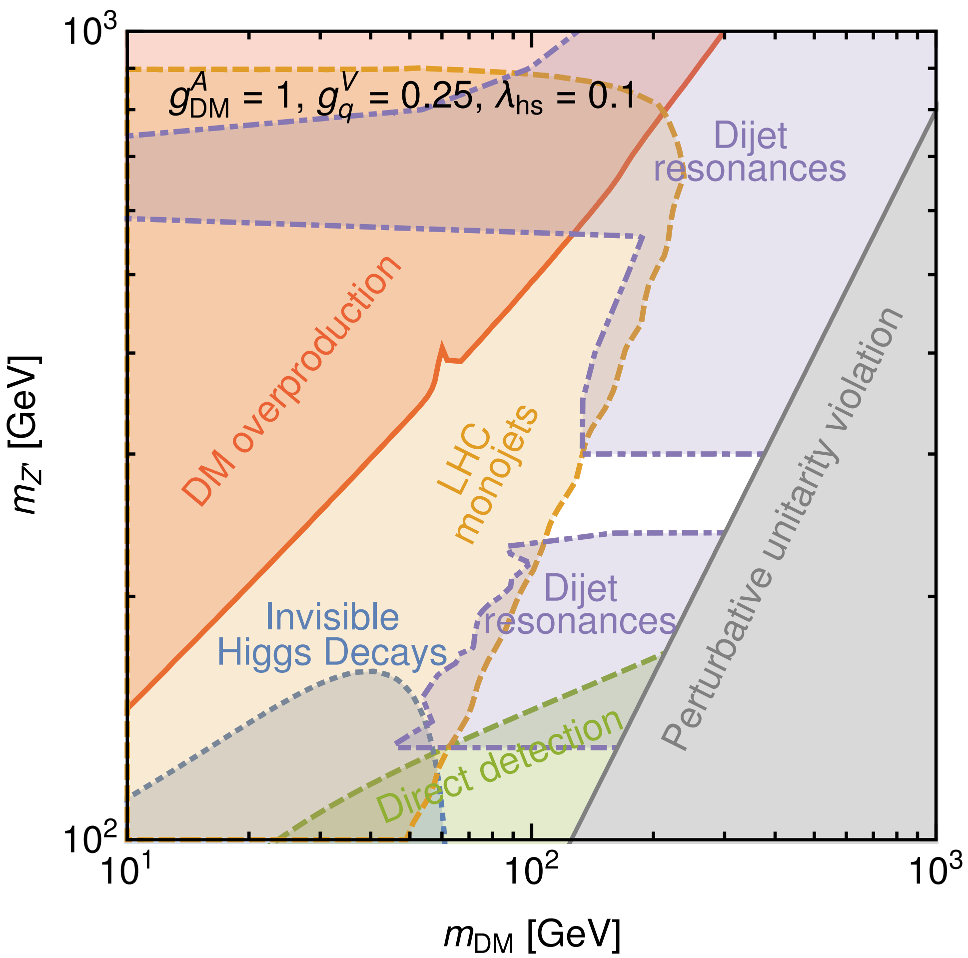
$$\mathcal{L} = -\sum_{f=q,l,\nu} Z'^{\mu}\,\bar{f}\left[g_f^V\gamma_\mu + g_f^A\gamma_\mu\gamma^5\right]f - Z'^{\mu}\,\bar{\psi}\left[g_{\rm DM}^V\gamma_\mu + g_{\rm DM}^A\gamma_\mu\gamma^5\right]\psi$$



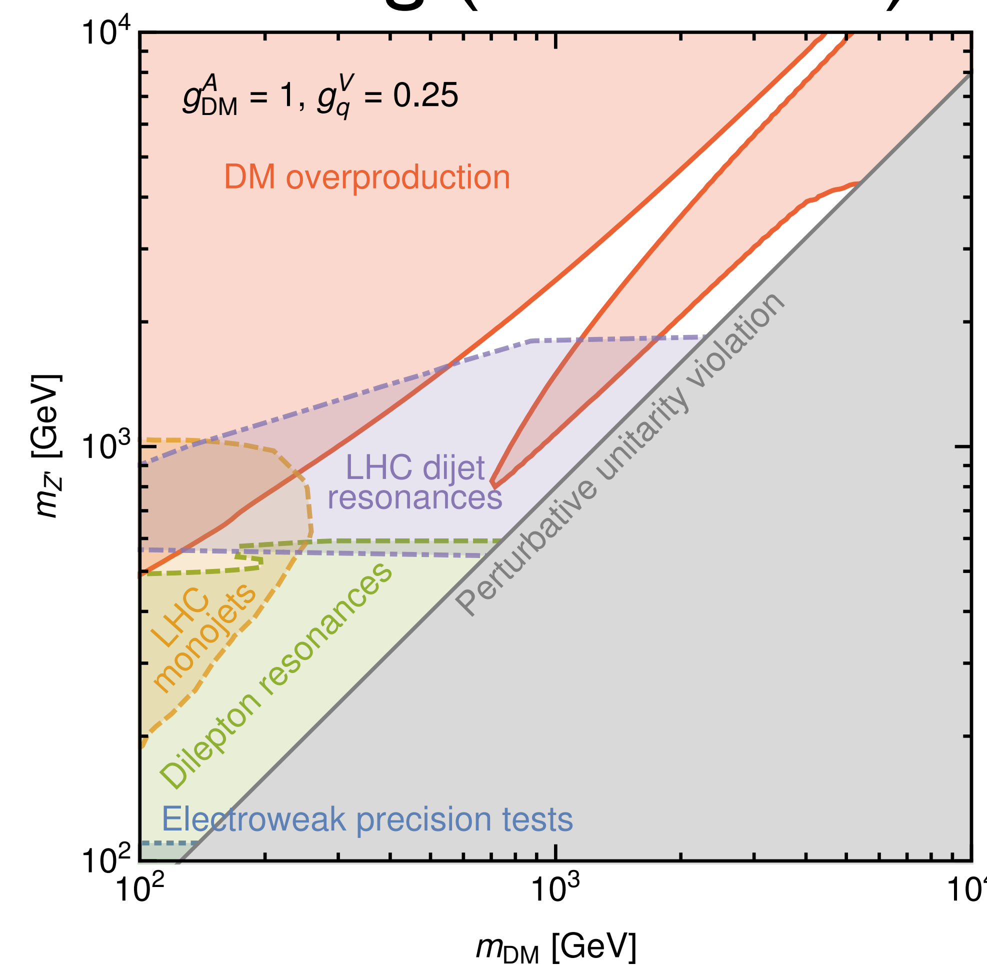
Effect of additional „portals“

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

Higgs-portal



loop induced kinetic mixing (Λ = 10 TeV)



Secluded WIMP 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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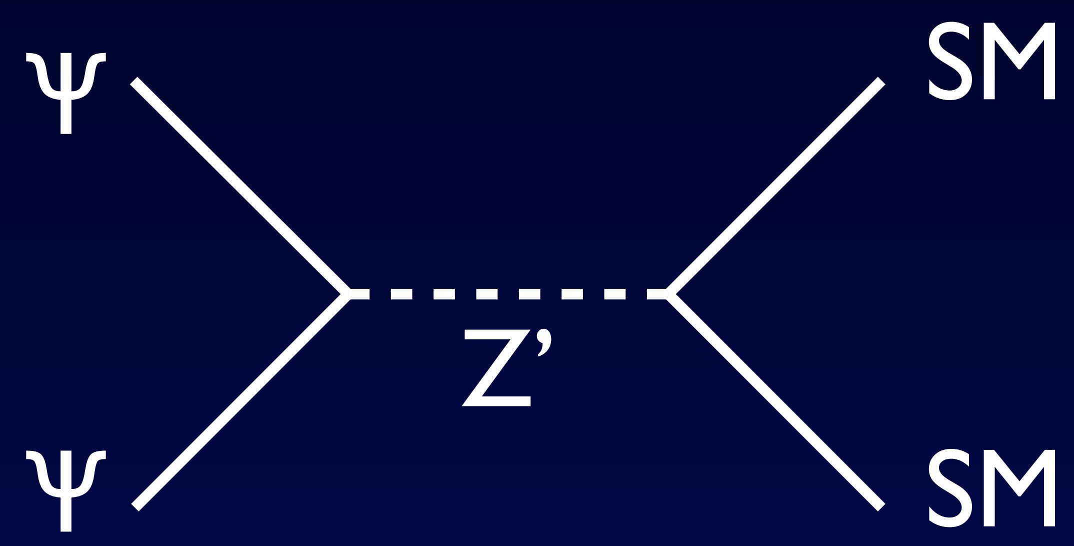

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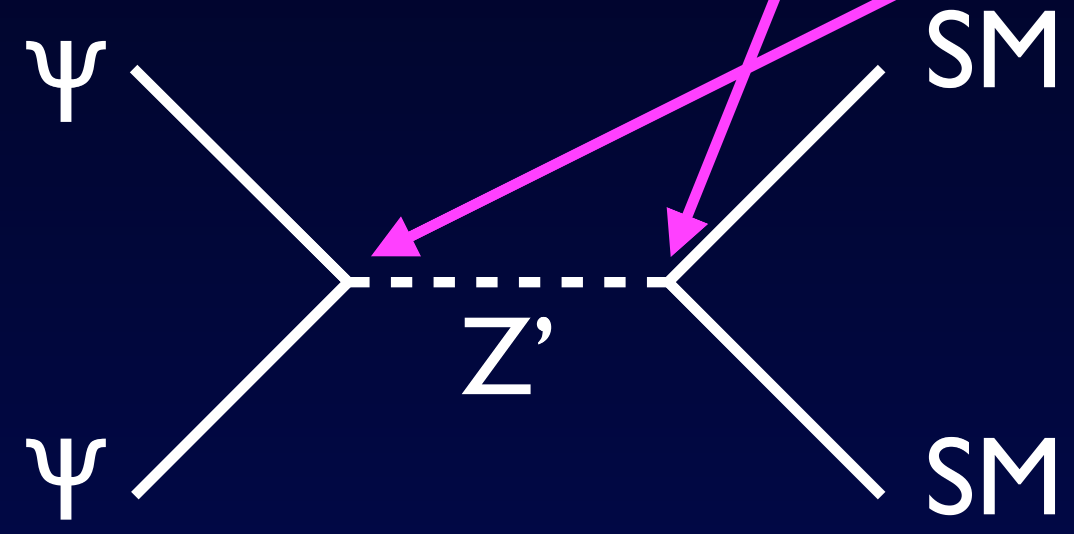

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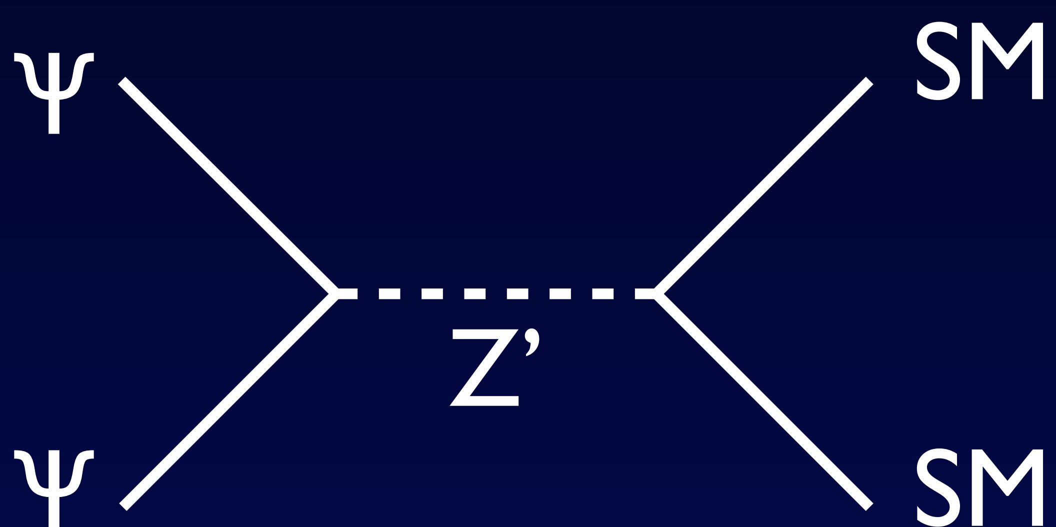
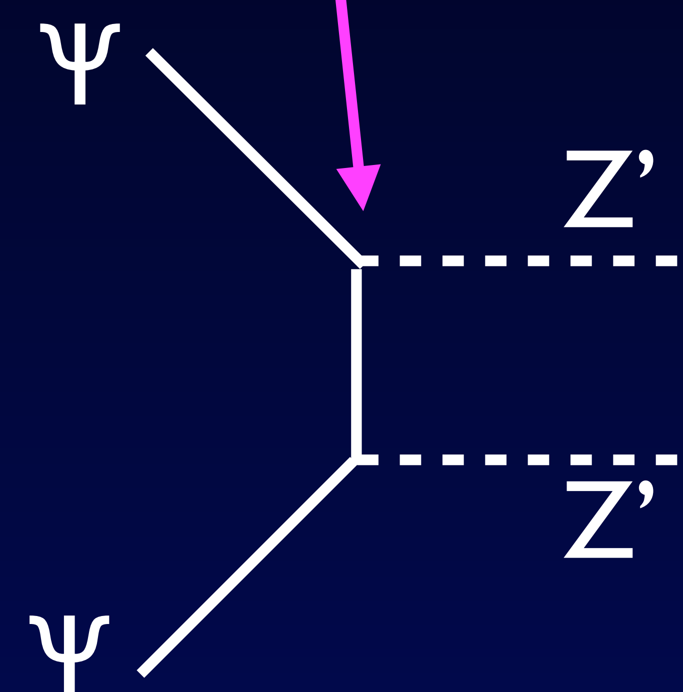
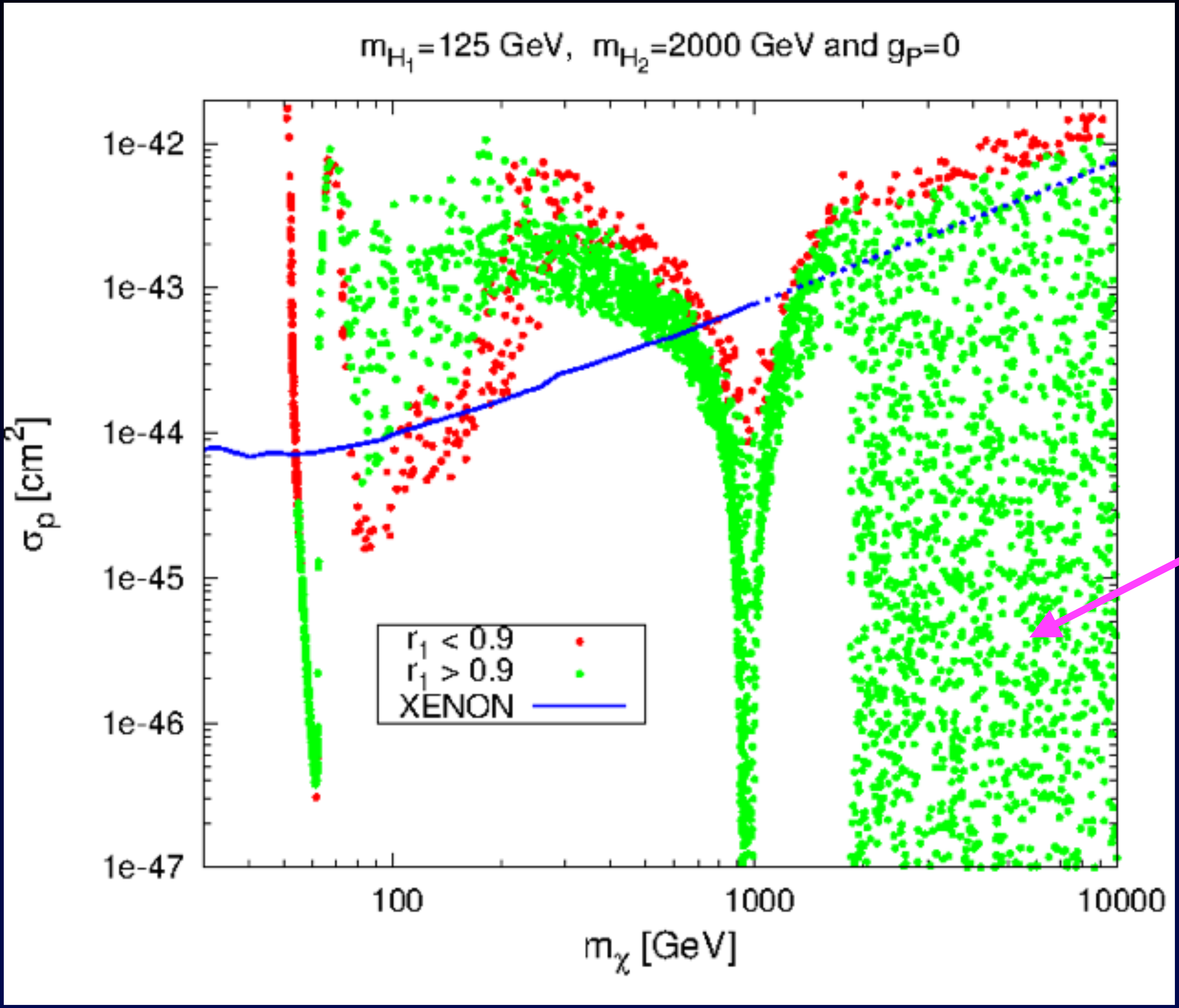
$m_{DM} > m_{Z'}$





Secluded WIMP DM



example with scalar mediator

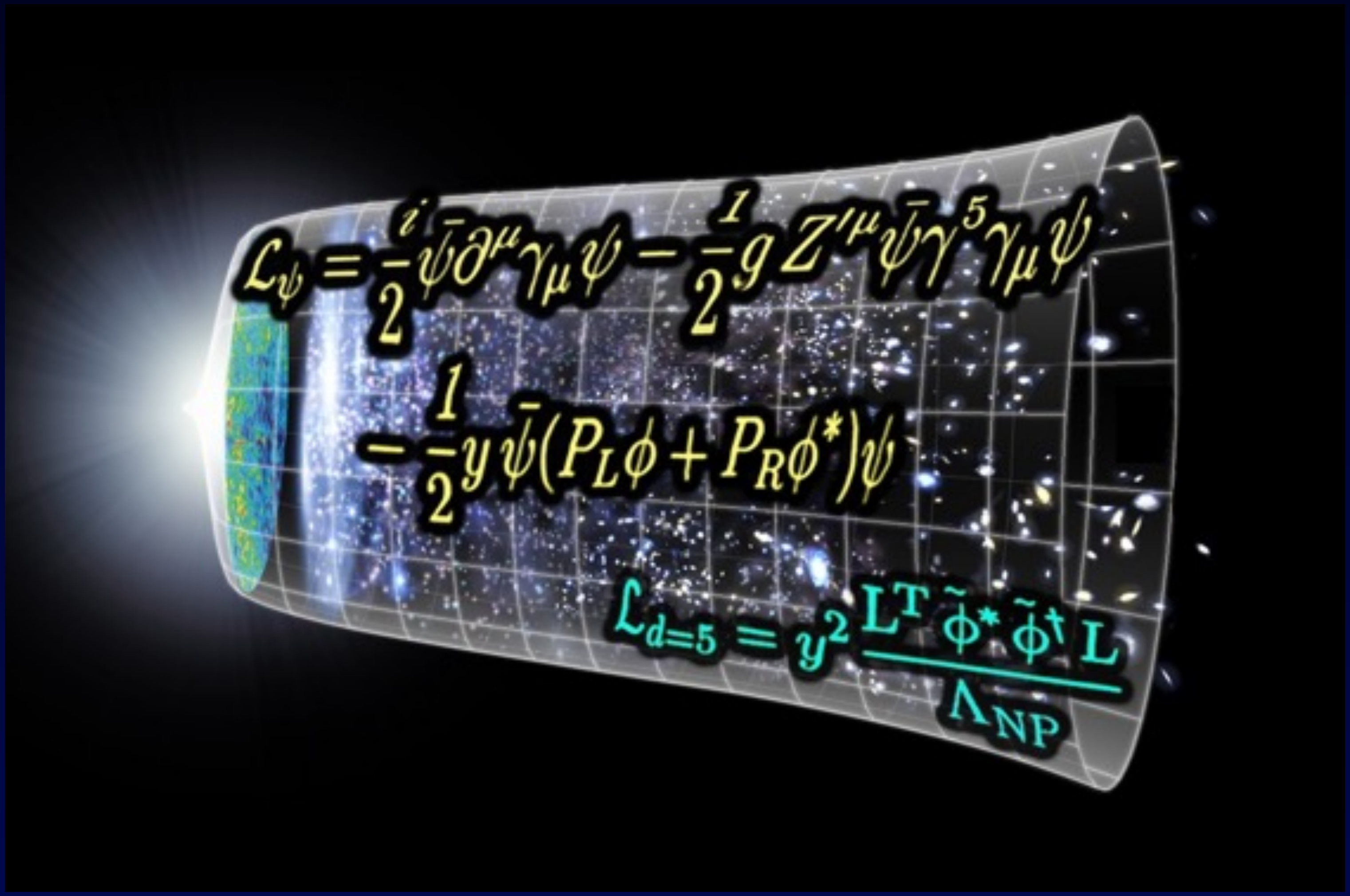
secluded region

Lopez-Honorez, TSM, Zupan, 12

Conclusions

- DM provides a challenge for particle physics - many possible DM candidates
- thermally produced DM (WIMP) is crucially tested by direct, indirect, and LHC searches
- next years will increase pressure on the WIMP hypothesis - or maybe find a signal (!)
- thermal WIMPs are hard (impossible?) to exclude
- a non-detection in ~5 years will make non-WIMP candidates more attractive

Thank you!



$\mathcal{L}_\psi = \frac{i}{2}\bar{\psi}\partial^\mu\gamma_\mu\psi - \frac{1}{2}g Z'^\mu\bar{\psi}\gamma^5\gamma_\mu\psi$
$-\frac{1}{2}y\bar{\psi}(P_L\phi + P_R\phi^*)\psi$
$\mathcal{L}_{d=5} = y^2\frac{L^T\tilde{\phi}^*\tilde{\phi}^\dagger L}{\Lambda_{NP}}$

additional slides

smaller DM couplings

Kahlhoefer, Schmidt-Hoberg, Schwetz, Vogl, 1510.02110

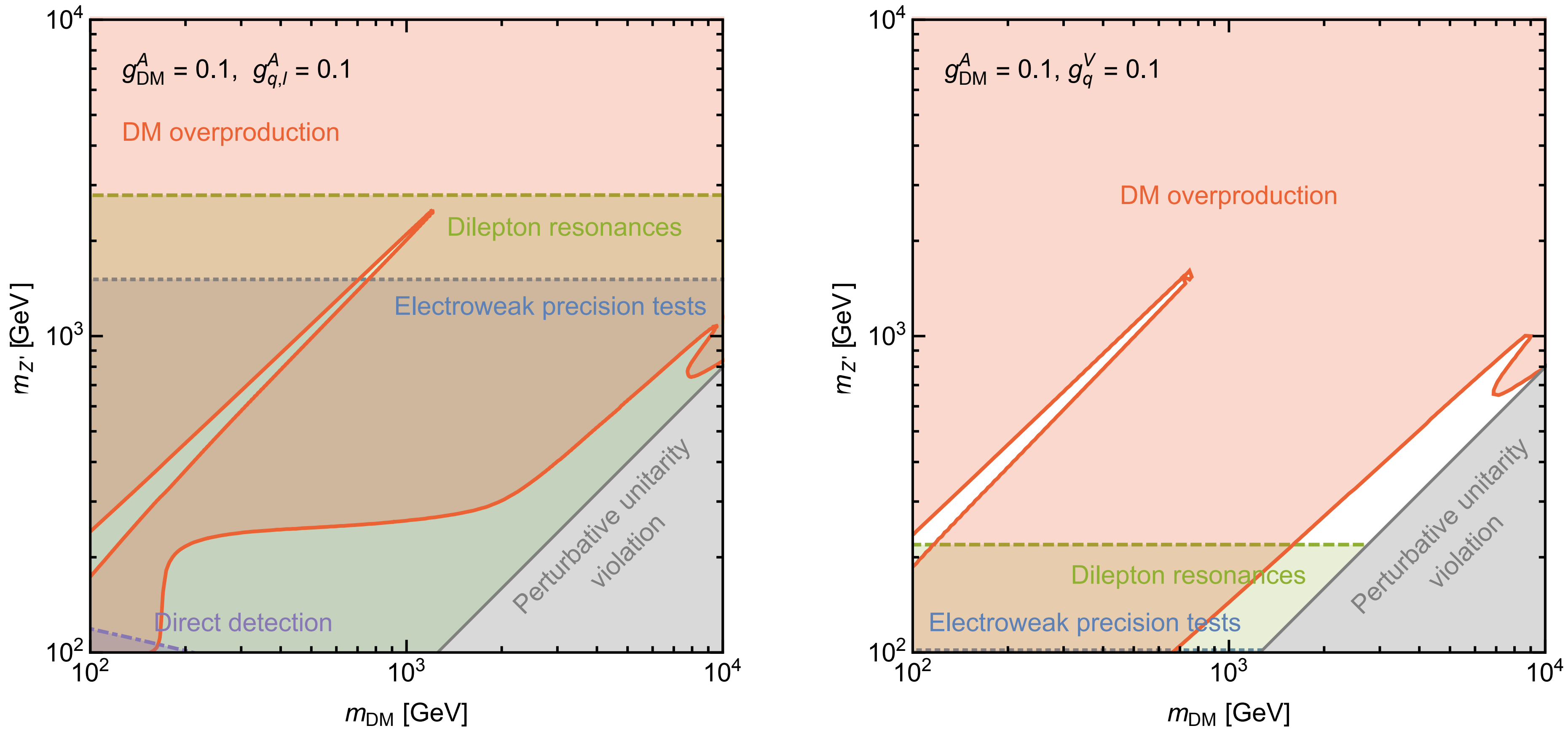
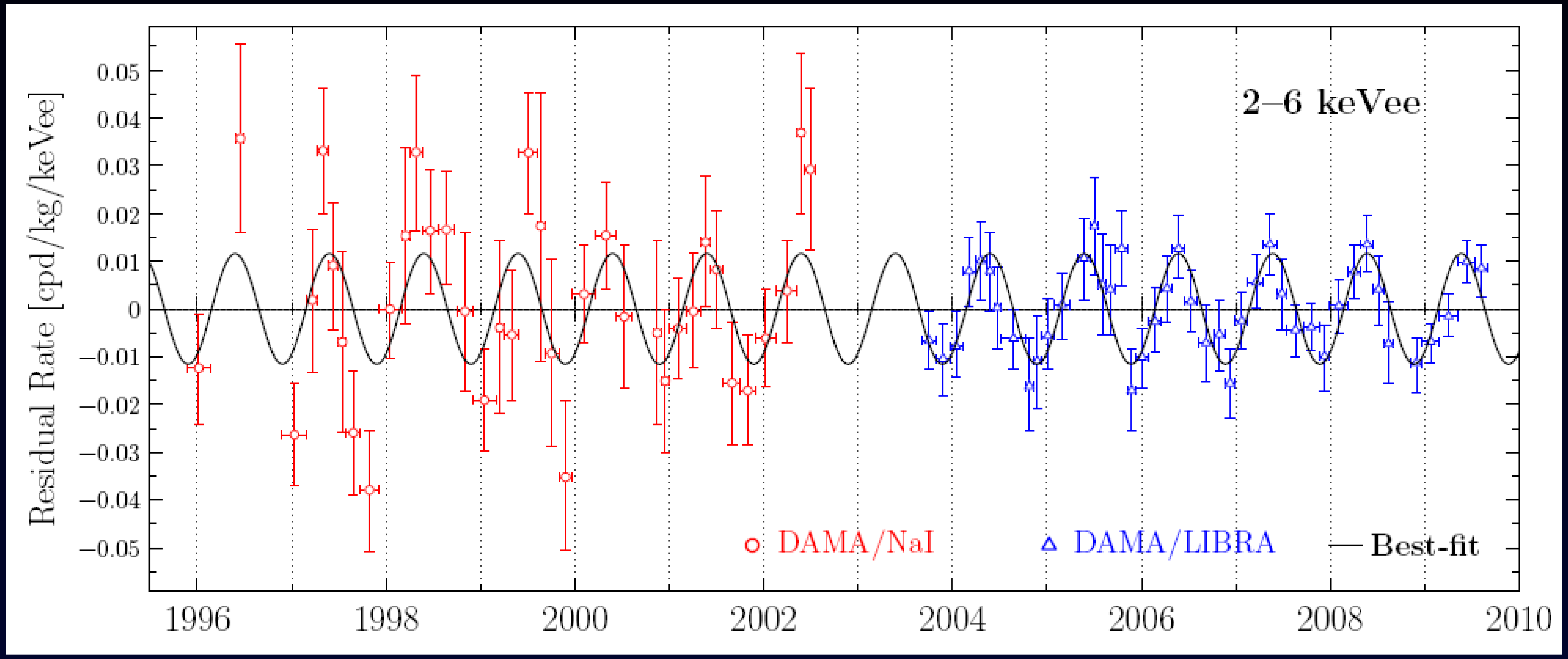
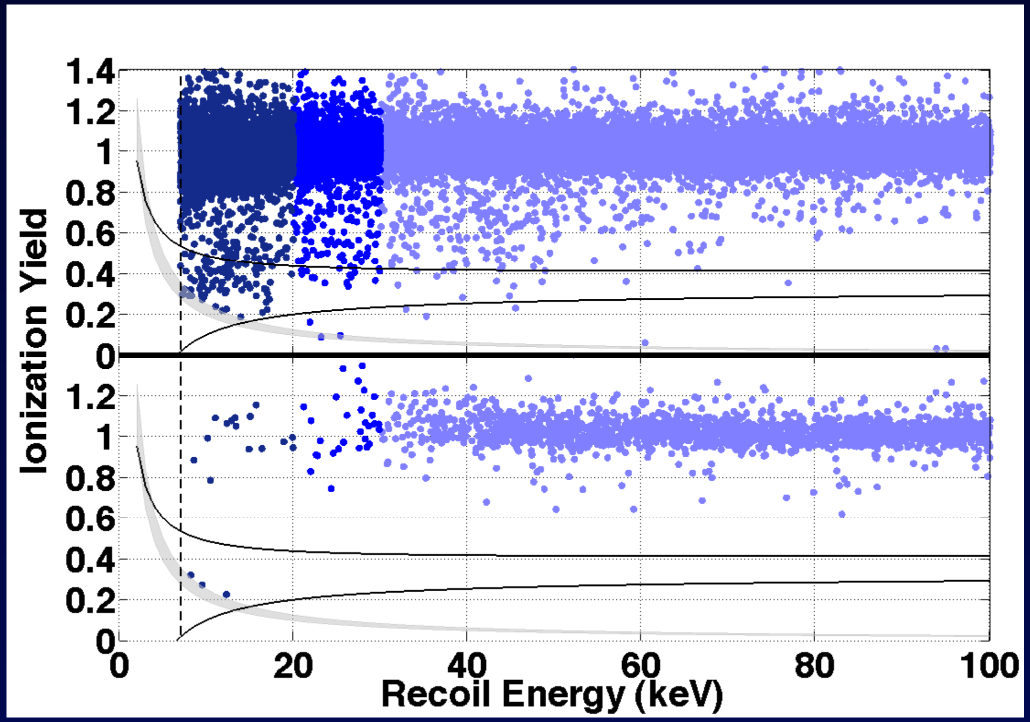


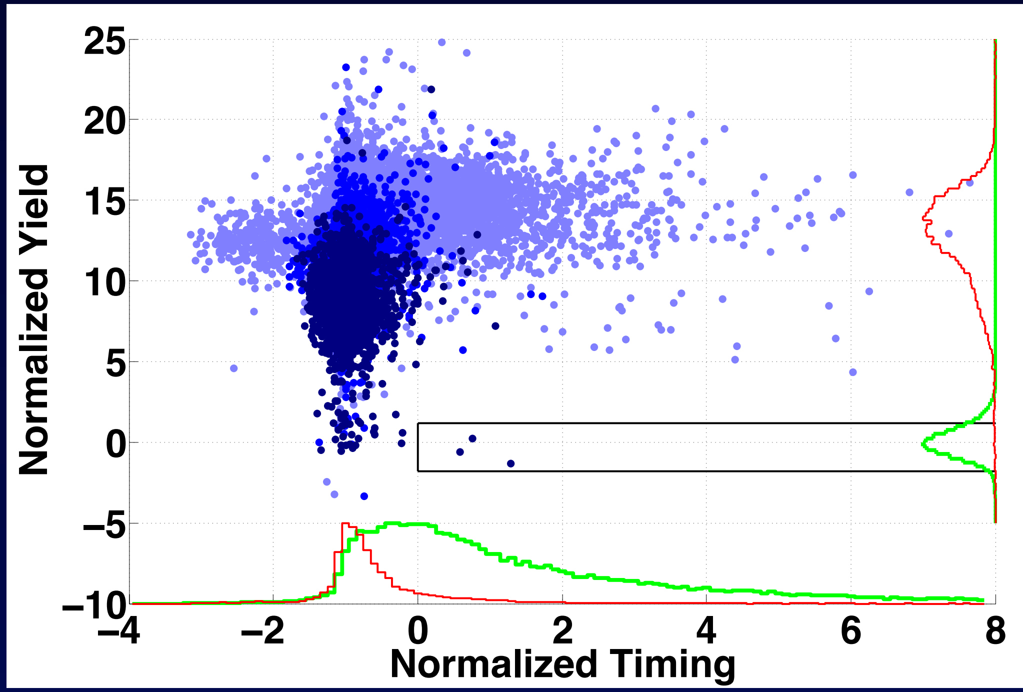
Figure 7. Constraints for small DM couplings ($g^A_{\mathrm{DM}} = 0.1$). The left panel considers the case Axial+Vector(SM)–Axial(DM) and should be compared to figure 4. The right panel considers the case Vector(SM)–Axial(DM) with loop-induced kinetic mixing, assuming that $\epsilon = 0$ at $\Lambda = 10\,\mathrm{TeV}$ (cf. figure 6).

DAMA modulation & CDMS-Si



DAMA/LIBRA

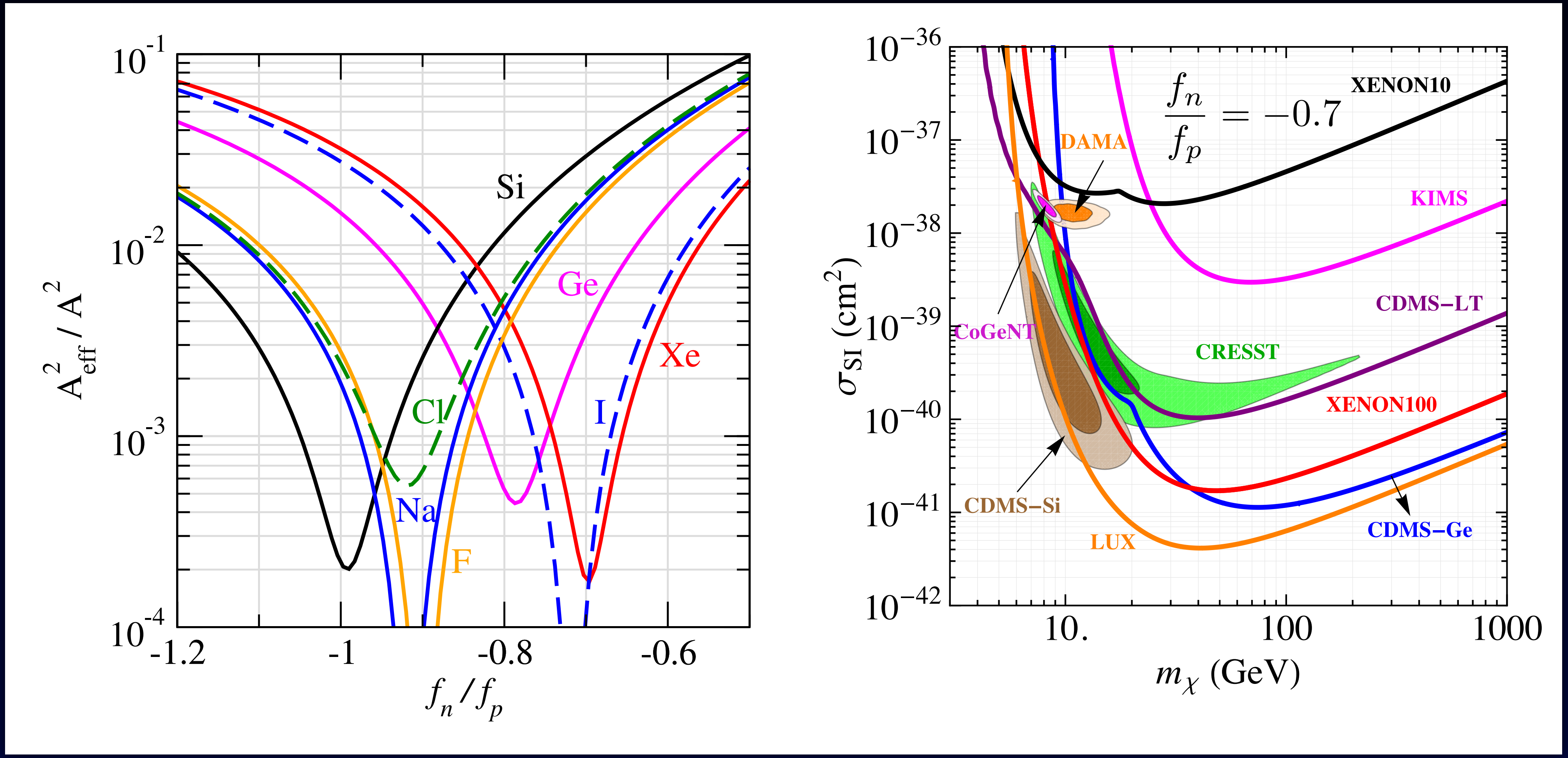




CDMS
1304.4279

Modified DM-nucleus interaction?

Ex.: negative interference between neutron and proton amplitudes



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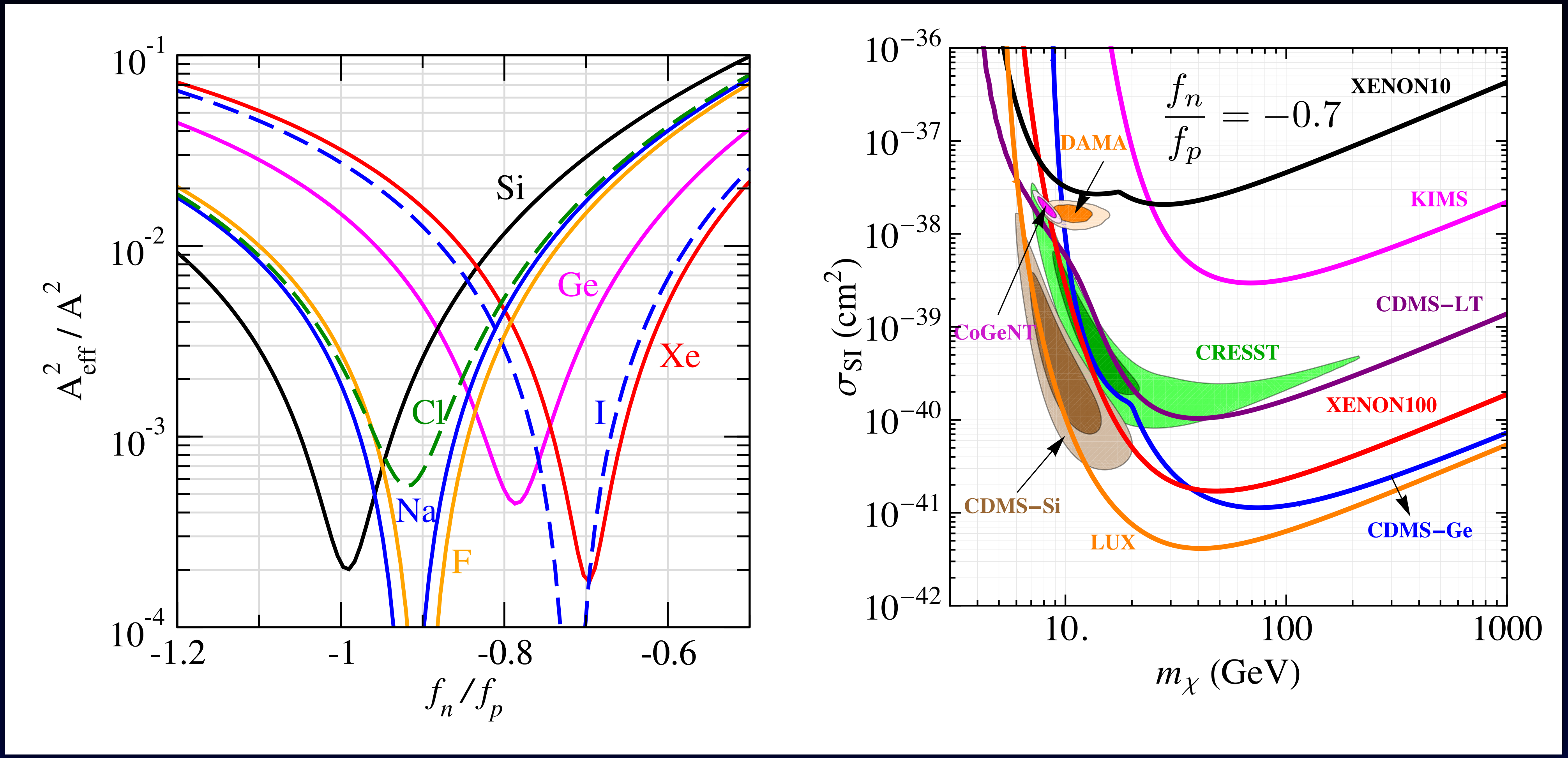


more examples:

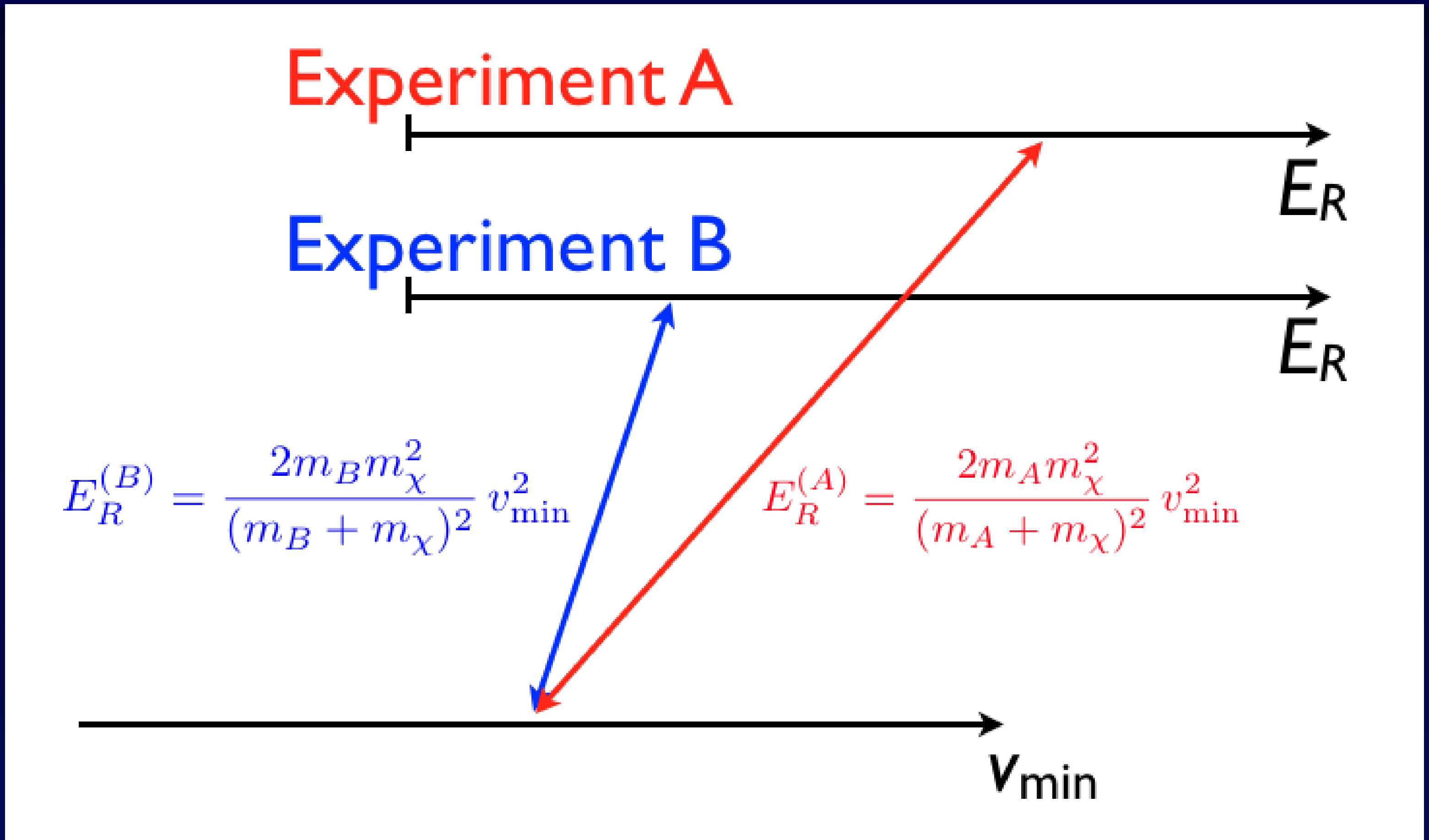
- inelastic scattering
- light mediator particles
- electromagnetic interact.

DM-halo independent comparison of experiments

$$\frac{dN}{dE_R} = \frac{\rho_\chi \sigma_0 |F(E_R)|^2}{2 m_\chi \mu^2} \eta(v_{\min}) \quad \text{with} \quad \eta(v_{\min}) \equiv \int_{v>v_{\min}} d^3v \, \frac{f_\oplus(\vec{v})}{v}$$

consider now

$$\boxed{\frac{2 m_\chi \mu^2}{\sigma_0 |F(E_R)|^2} \frac{dN}{dE_R} = \rho_\chi \, \eta(v_{\min})}$$

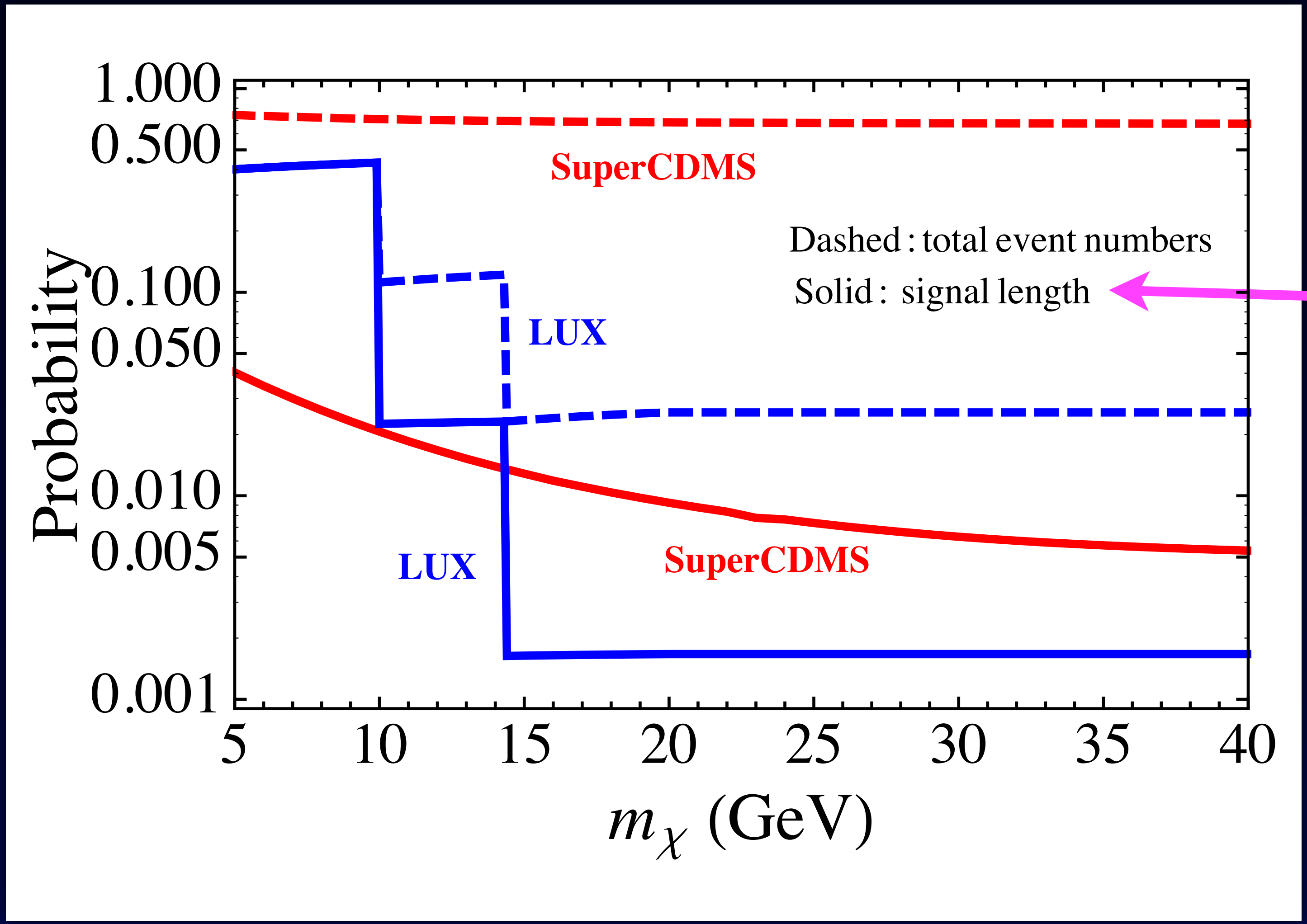


$$v_{\min} = \sqrt{\frac{E_R m_A}{2\mu^2}}$$

Fox, Kribs, Tait, 2010
Fox, Liu, Weiner, 2010

DM-halo independent comparison - CDMS-Si versus LUX / SuperCDMS

joint probability for CDMS-Si and LUX / SuperCDMS



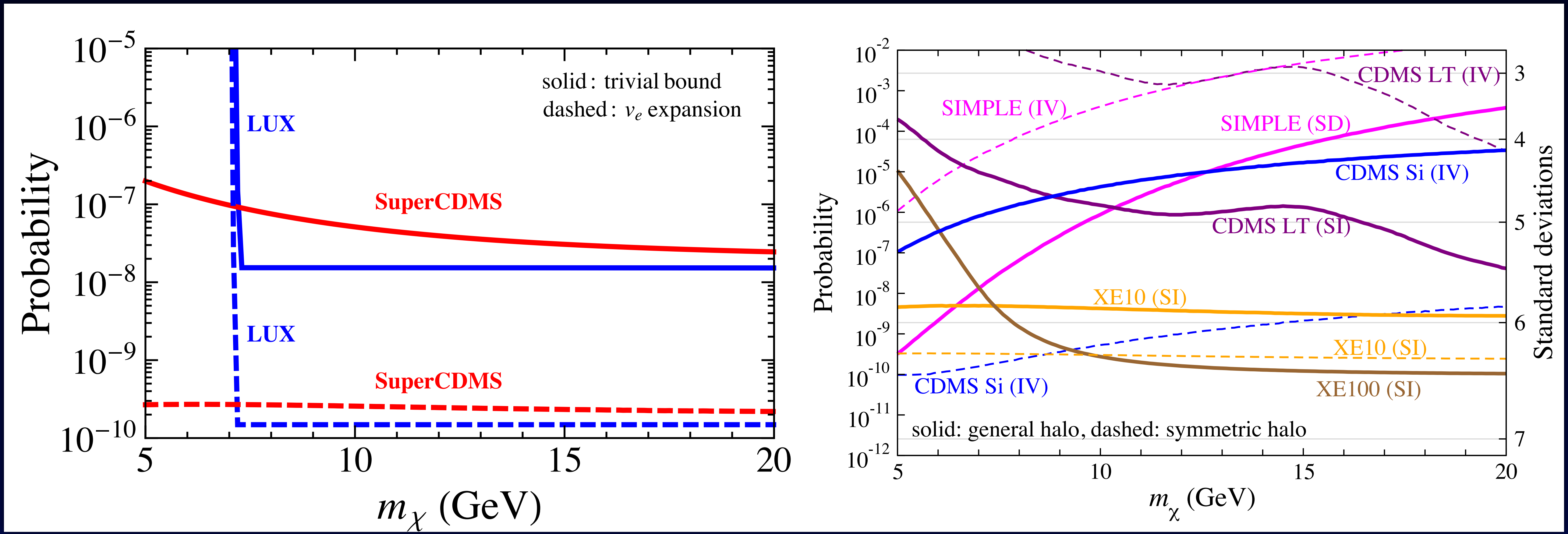
takes into account energy information from the 3 Si events

Bozorgnia, Schwetz, 1410.6160

DM-halo independent comparison - DAMA versus LUX / SuperCDMS / ...

joint probability for modulation amplitude in DAMA (3rd bin) and the LUX / SuperCDMS results

expansion in v_e



Bozorgnia, Schwetz, 1410.6160　　*Herrero-Garcia, Schwetz, Zupan, 2012*