Dark Model models

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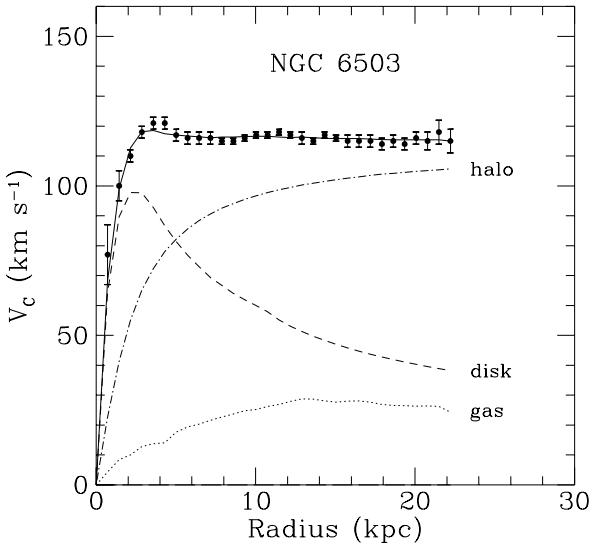
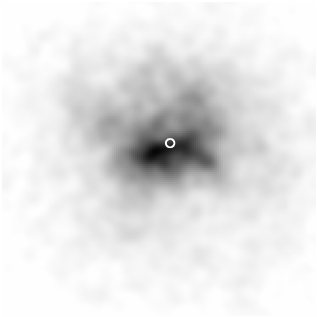
Dark Matter in astrophysics

Rotational curves



Gravitational lensing

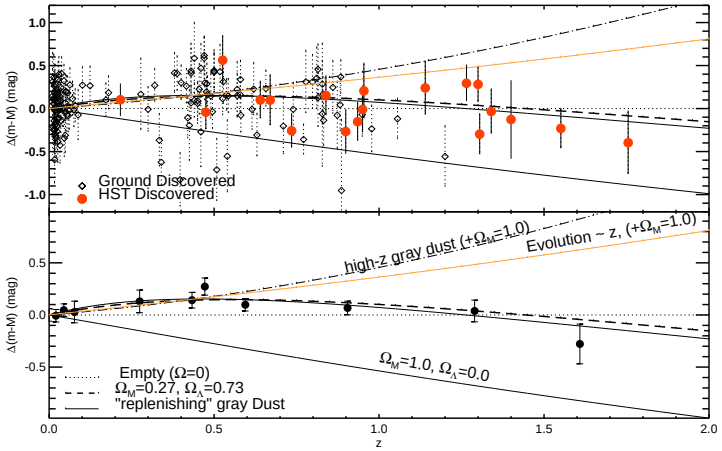


X-rays from centers of galaxy clusters

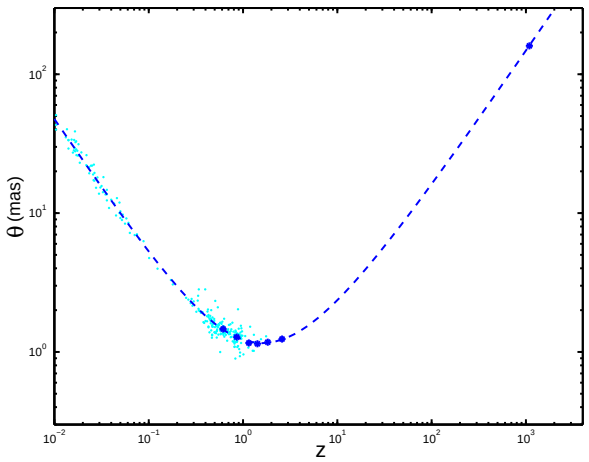
“Bullet” cluster

Dark matter in cosmology

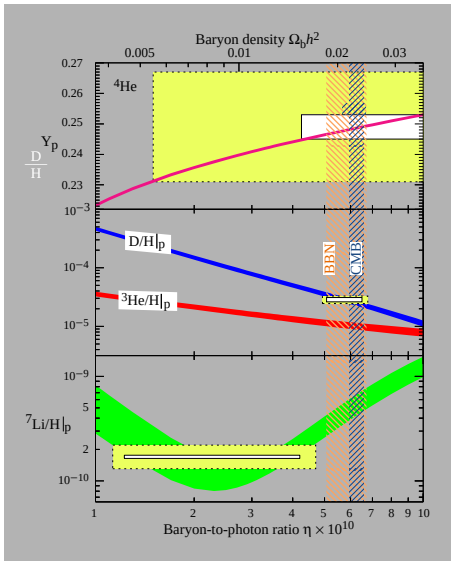
Standard candles

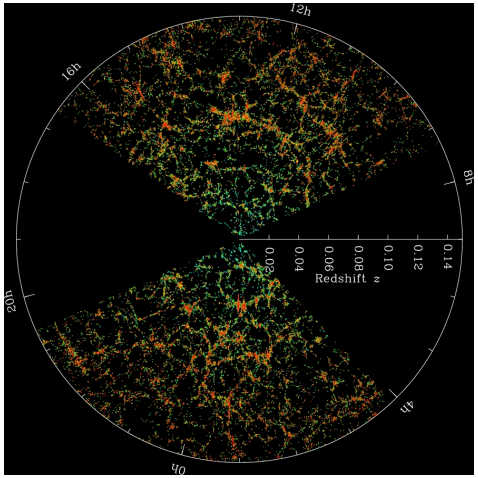


Angular distance

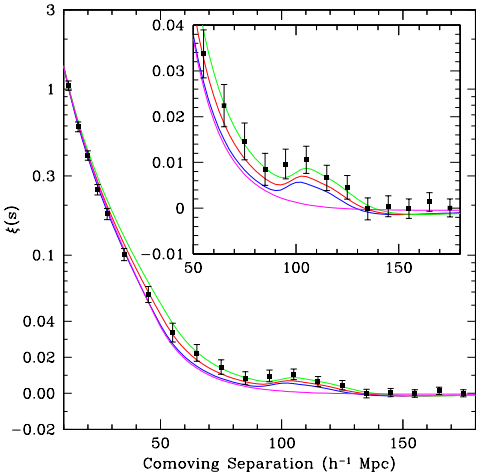


Nucleosynthesis

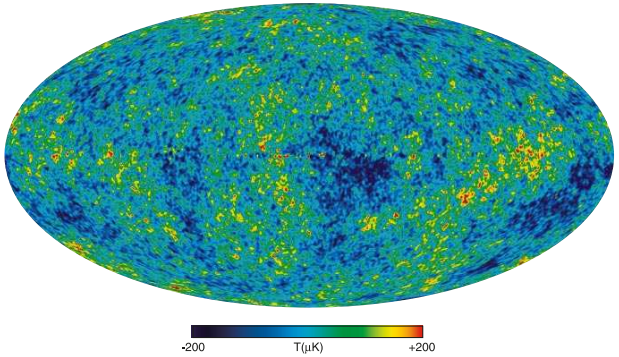




Large Scale Structures



Baryon acoustic oscillations



CMB anisotropy

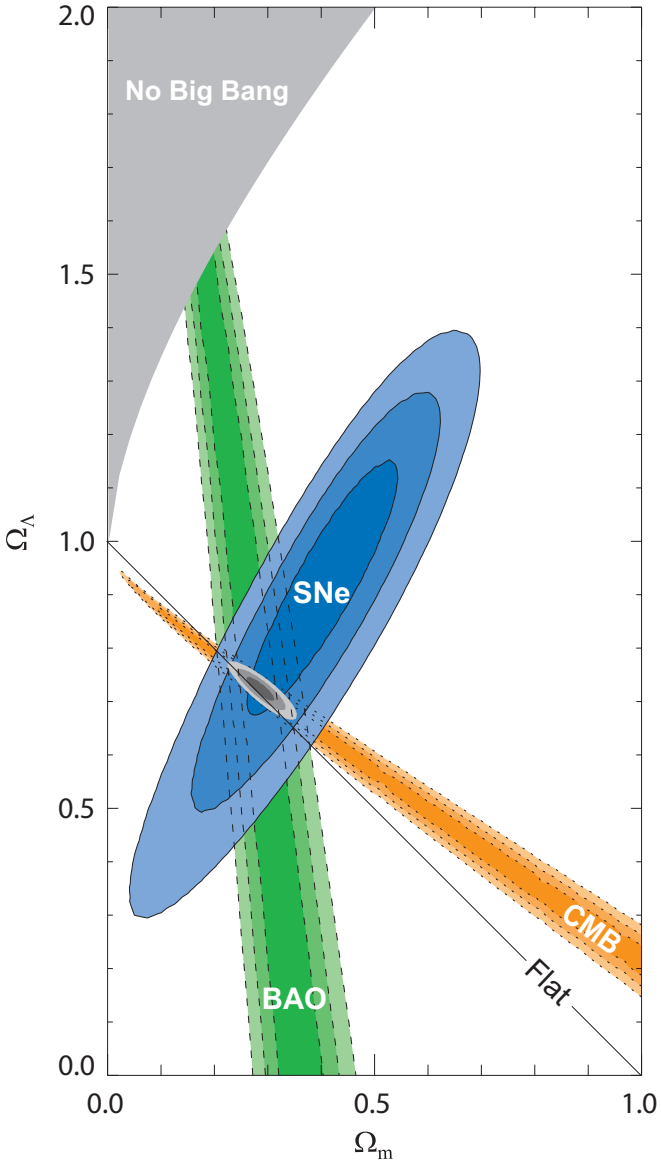
Dark Matter properties from cosmology: $p = 0$

(If) particles:

1. stable on cosmological time-scale
   requires new (almost) conserved quantum number
2. produced in the early Universe
   some time before RD/MD-transition ($T = 0.8\,\text{eV}$)
3. nonrelativistic particles long before RD/MD-transition ($T = 0.8\,\text{eV}$)
   (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
   Otherwise no small-size structures, like dwarf galaxies:
   smoothed out by free streaming
   If were in thermal equilibrium: $M_X \gtrsim 1$ keV
4. (almost) collisionless $p = 0$, $v_{\text{sound}} = 0$
5. (almost) electrically neutral CMB distortion
6. all matter inhomogeneities (perturbations) are adiabatic:

$$\delta\left(\frac{n_B}{n_{DM}}\right) = \delta\left(\frac{n_B}{n_\gamma}\right) = \delta\left(\frac{n_\nu}{n_\gamma}\right) = 0$$

Astrophysical and cosmological data are in agreement



$$\left(\frac{\dot{a}}{a}\right)^2 = H^2(t) = \frac{8\pi}{3} G \rho^{\text{energy}}_{\text{density}}$$

$$\rho^{\text{energy}}_{\text{density}} = \rho_{\text{radiation}} + \rho^{\text{ordinary}}_{\text{matter}} + \rho^{\text{dark}}_{\text{matter}} + \rho_\Lambda$$

$$\rho_{\text{radiation}} \propto 1/a^4(t)\,, \quad \rho_{\text{matter}} \propto 1/a^3(t)\,, \quad \rho_\Lambda = \text{const}$$

$$\frac{3H_0^2}{8\pi G} = \rho^{\text{energy}}_{\text{density}}(t_0) \equiv \rho_c \approx 0.53 \times 10^{-5}\,\frac{\text{GeV}}{\text{cm}^3}$$

Radiation: $\Omega_\gamma \equiv \frac{\rho_\gamma}{\rho_c} = 0.5 \times 10^{-4}$

Baryons (H, He): $\Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.05$

Neutrino: $\Omega_\nu \equiv \frac{\sum \rho_{\nu_i}}{\rho_c} < 0.01$

$N_\nu \simeq 3\,,\ \sum m_\nu \lesssim 0.3\,\text{eV}$

Dark matter: $\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_c} = 0.27$

Dark energy: $\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.68$

Interplay: Standard Model and Cosmology

Gauge fields (interactions): γ, $W^{\pm}$, Z, g

Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$, d_R, u_R

- SM Describes
  - all experiments dealing with electroweak and strong interactions
- SM fails to describe (PHENO) (THEORY)
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry (Ω_B)
  - Inflationary stage
  - Dark energy (Ω_Λ)
  - Strong CP-problem
  - Gauge hierarchy
  - Quantum gravity

And hence asks for new physics

Weakly Interacting Massive Particles

Assumptions:

1. X and $\bar{X}$ are stable (at cosmological time scale)
2. no $X - \bar{X}$ asymmetry $\qquad n_X = n_{\bar{X}}$
3. @ $T < M_X$ in thermal equilibrium with plasma

$$n_X = n_{\bar{X}} = g_X \left(\frac{M_X T}{2\pi} \right)^{3/2} e^{-M_X/T}$$

$$X\bar{X} \longleftrightarrow \text{light particles}$$

Bethe formulae: s-wave: $\sigma_{ann} = \frac{\sigma_0}{v}$

$X + \bar{X}$ contribution to critical density:

$$\Omega_X = 0.1 \times \frac{(1\ \text{TeV})^{-2}}{100 \times \sigma_0} \frac{0.3}{\sqrt{g_*(T_f)}} \ln \left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}} \right) \cdot \frac{1}{2h^2}$$

WIMPs: discussion

$$\Omega_X = 0.1 \cdot \left(\frac{(10\ \text{TeV})^{-2}}{\sigma_0} \right) \frac{10}{\sqrt{g_*(T_f)}} \ln \left(\frac{g_X M_{\text{Pl}}^* M_X \sigma_0}{(2\pi)^{3/2}} \right) \cdot \frac{1}{2h^2}$$

- natural DM: subweak-scale cross section $\sigma_0 \sim 0.01 \times \sigma_W$
  say, $M_X \sim 1$ TeV annihilate through t-channel $XX \to ZZ$
  or X is not a weak gauge eigenstate, $g_W \to g_W \times \sin\xi$
- naturaly "light" unitarity $\sigma_0 \lesssim \frac{4\pi}{M_X^2} \longrightarrow M_X \lesssim 100$ TeV
- all stable particles with smaller σ_0 are forbidden !!
- WIMPs remain in kinetic equilibrium with plasma till $T \sim 10$ MeV

this is Cold Dark Matter, $v_{RD/MD} \ll 10^{-3}$

WIMPs may form dark halos (clumps) much lighter than

dwarf galaxies

Weakly IMPs are mostly welcome (e.g. LSP in SUSY)

We can fully explore the model !!

- Direct searches for Galactic Dark Matter ($v_X \sim 10^{-3}$)

$$X + \text{nuclei} \to X + \text{nuclei} + \Delta E$$

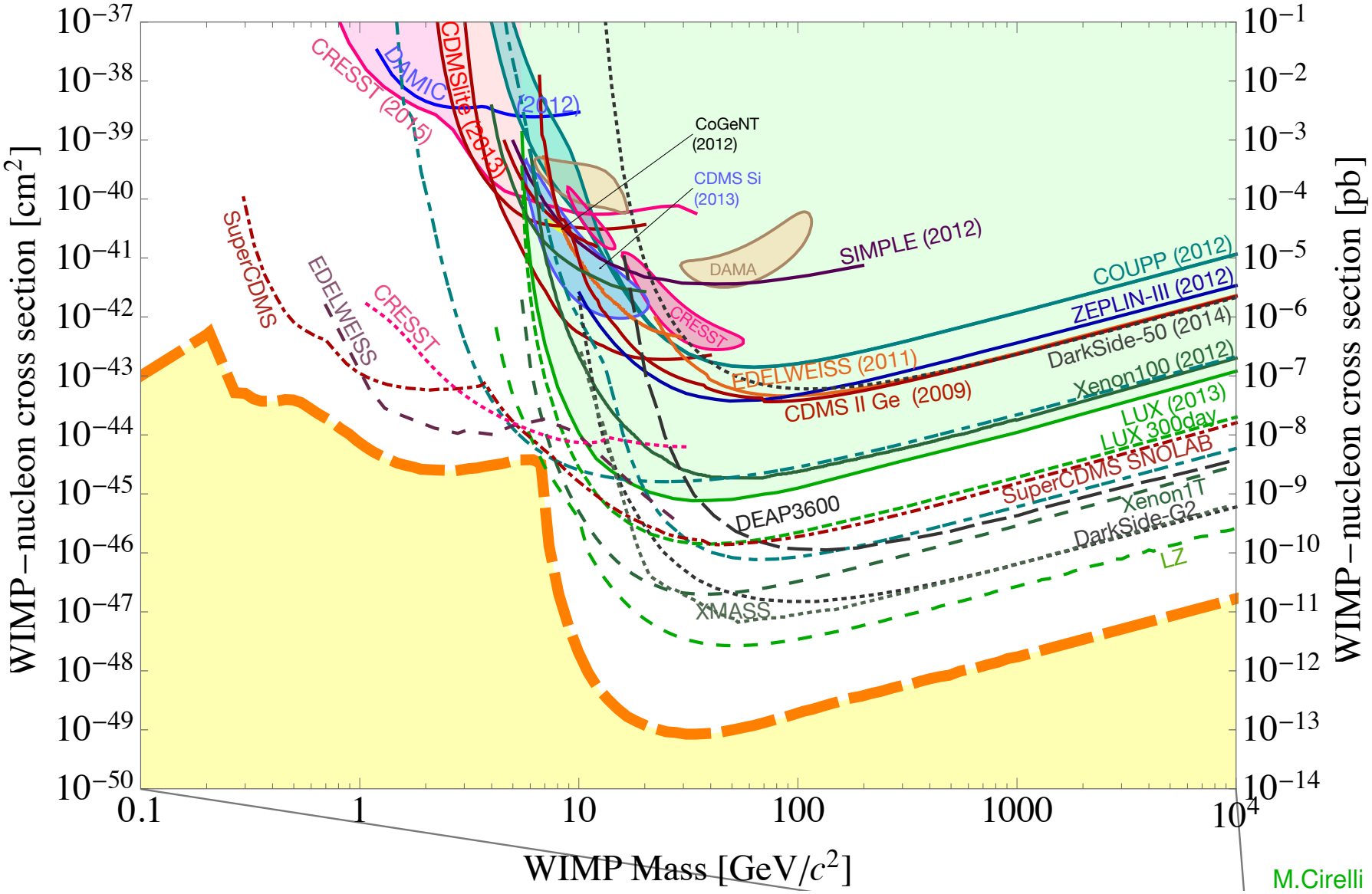
- Can search for WIMPs in cosmic rays: products of WIMPs annihilation (in Galactic center, dwarf galaxies, Sun)

$$X + \bar{X} \to p\bar{p}, \;\; e^+e^-, \;\; \nu\bar{\nu}, \gamma, \ldots$$

- Can search for WIMPs in collision experiments (LHC):

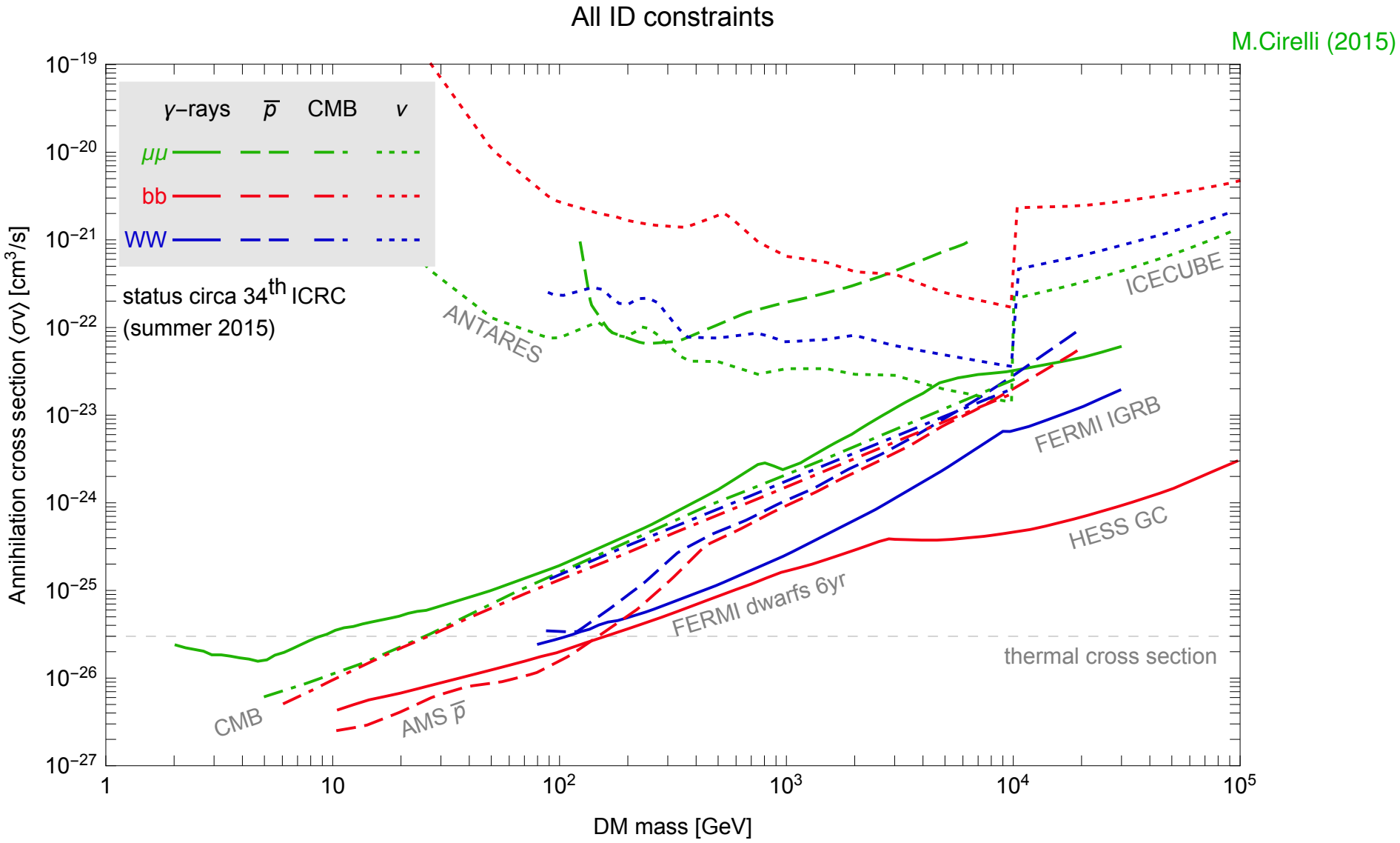
$$p + p \to X + \bar{X} + \text{SM} + \ldots$$

Prospects in WIMP searches



M.Cirelli (2015)

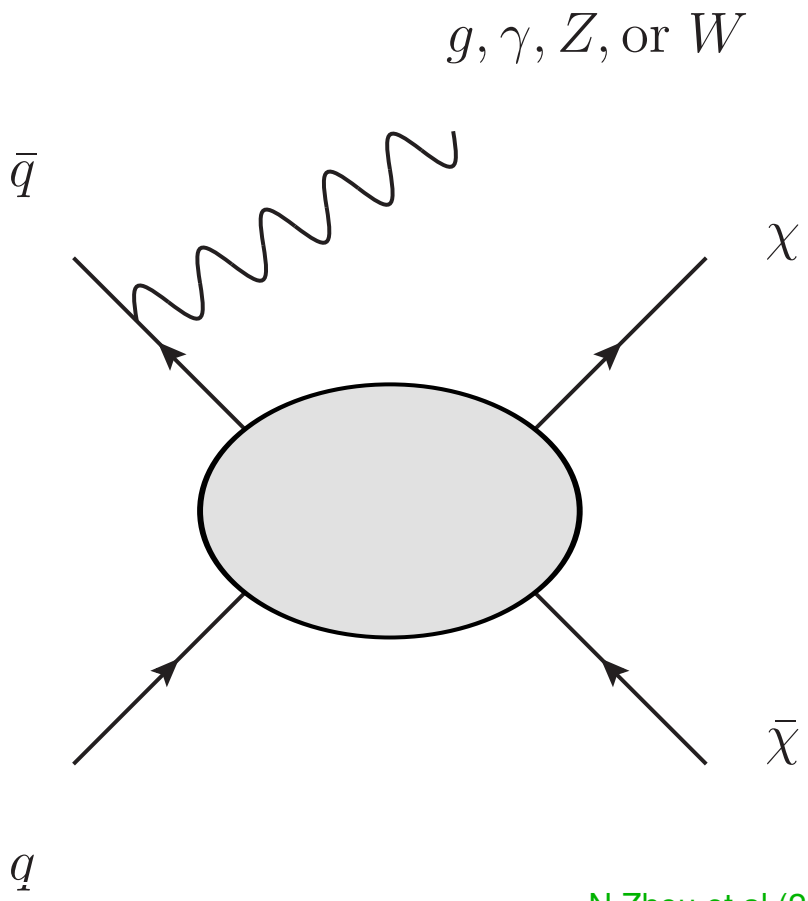
Present indirect limits on DM annihilation



Searches for DM particles at LHC ...

LHC helps!

Illustration with searches for WIMP-signal



N.Zhou et al (2013)

Logic: no light superpartners, $M_{SUSY} > 500\,\text{GeV}$

let's integrate them out to get low energy EFT

$$D1\ (\text{scalar}): \quad \frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$$

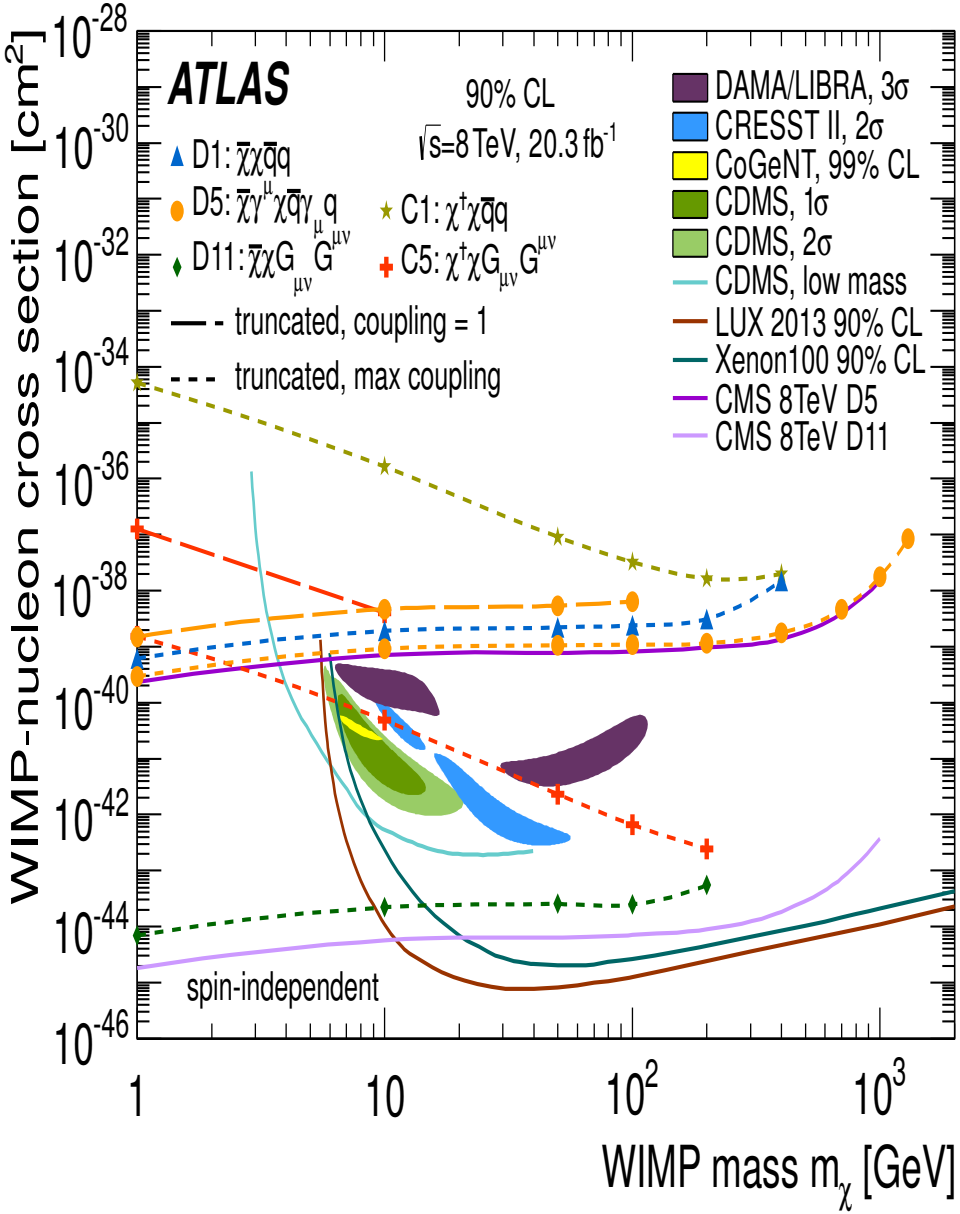
$$D8\ (\text{axial}): \quad \frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$$

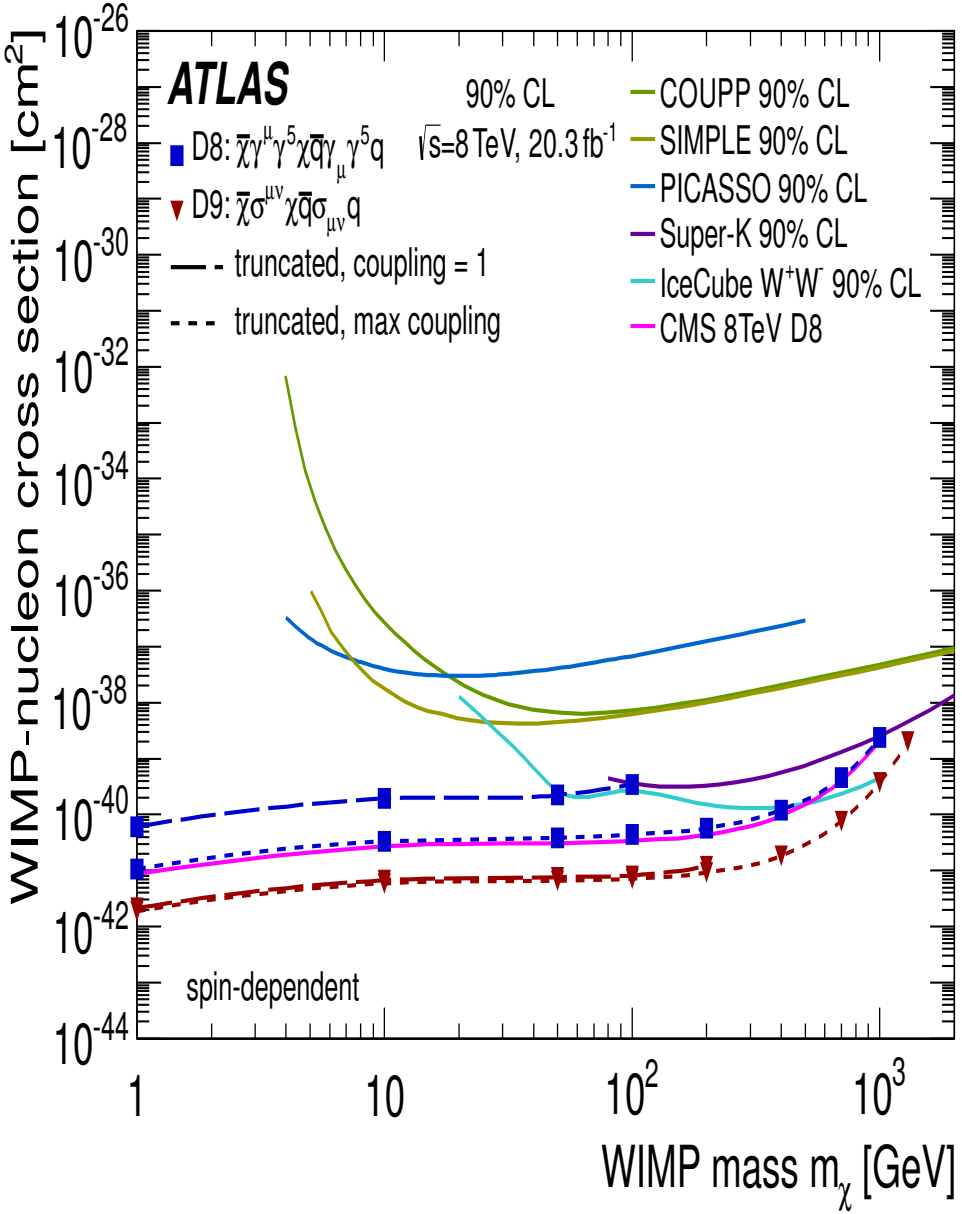
$$D5\ (\text{vector}): \quad \frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

$$D9\ (\text{tensor}): \quad \frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$$

suppressed by gauge couplings α_s, α, α_W, ...

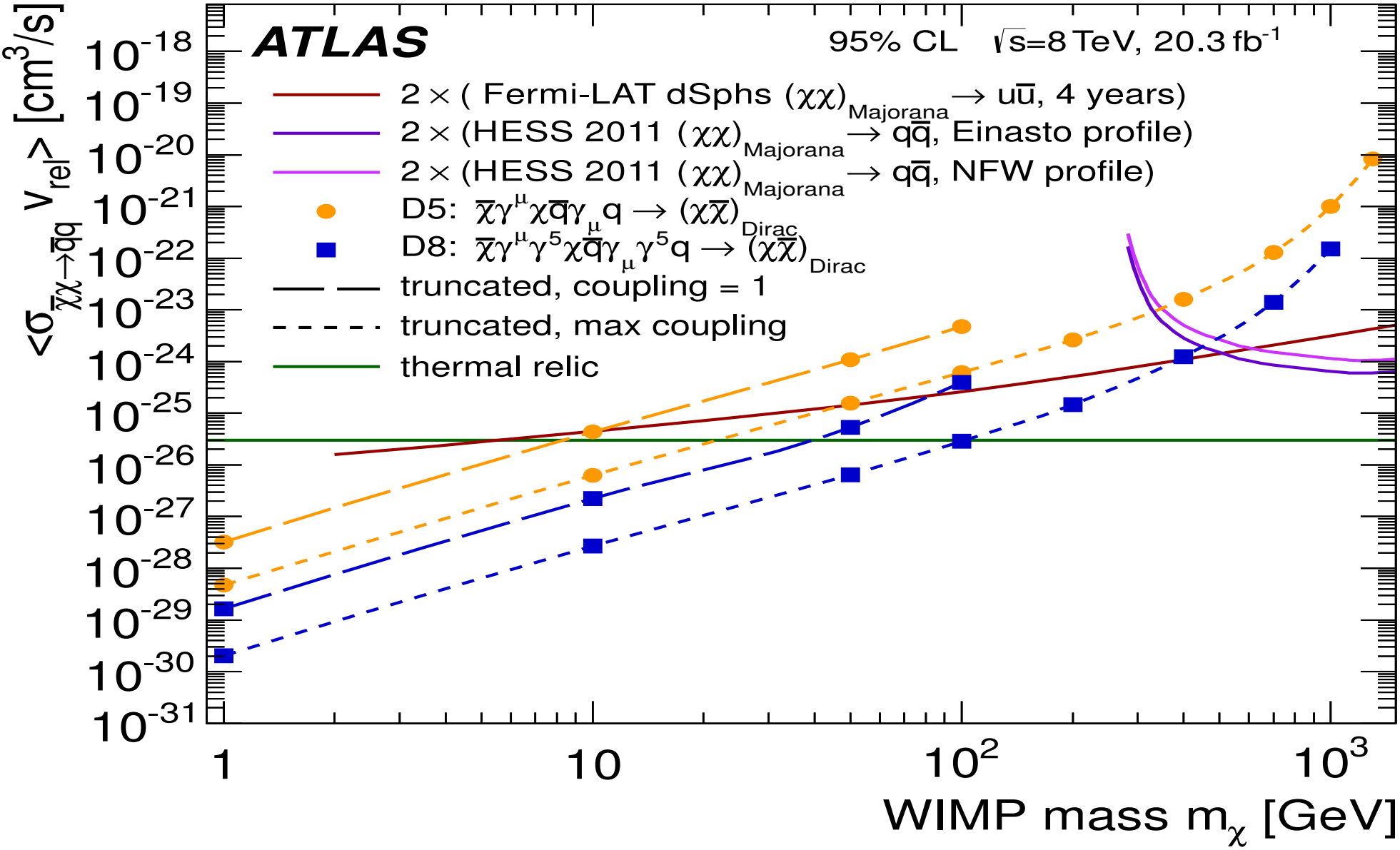
ATLAS and CMS results of searches at @ 8 TeV 1502.01518





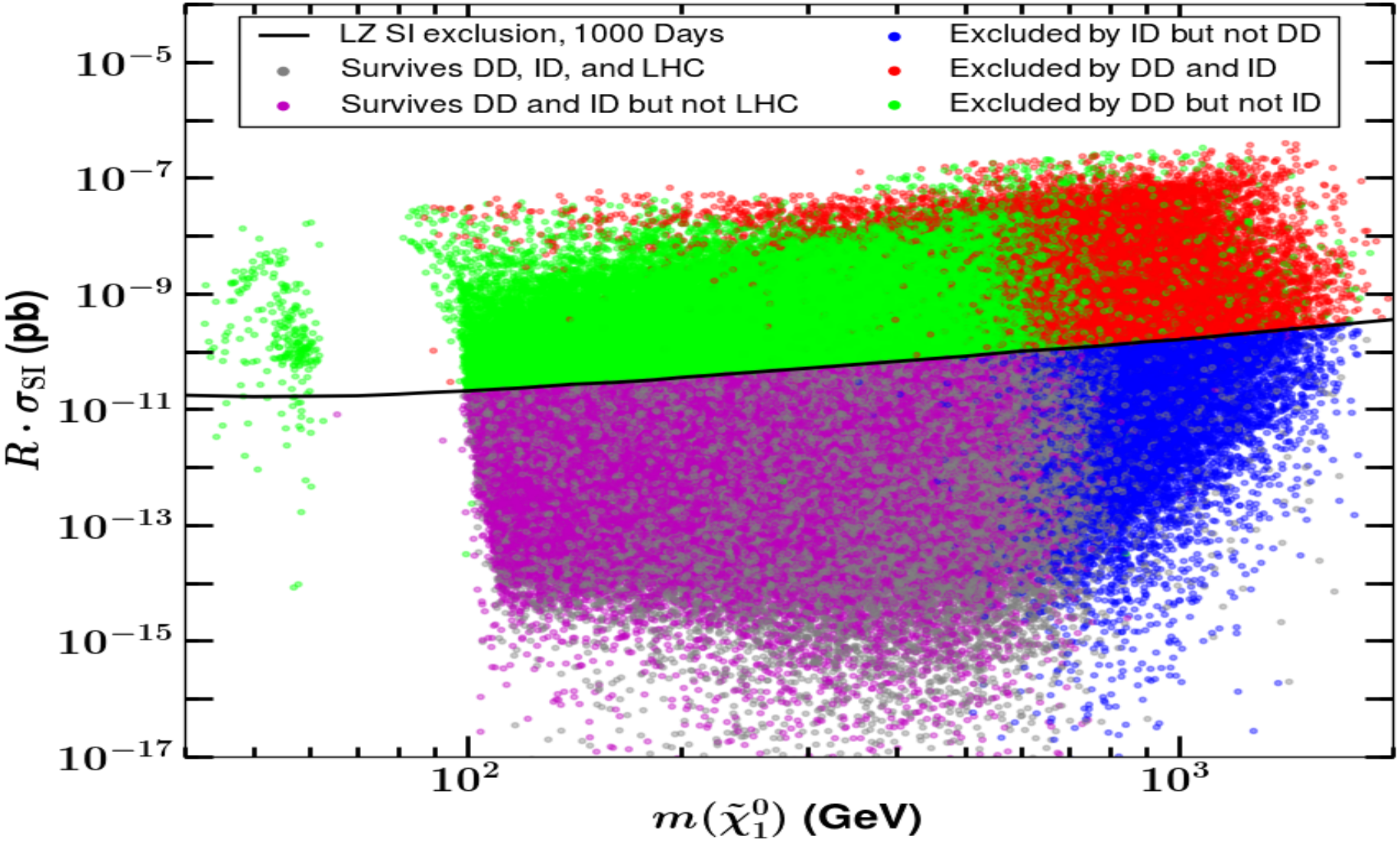
LHC limits for annihilation

1502.01518



Competition in testing MSSM

1405.6716



If thermal CDM but not Weakly IMPs?

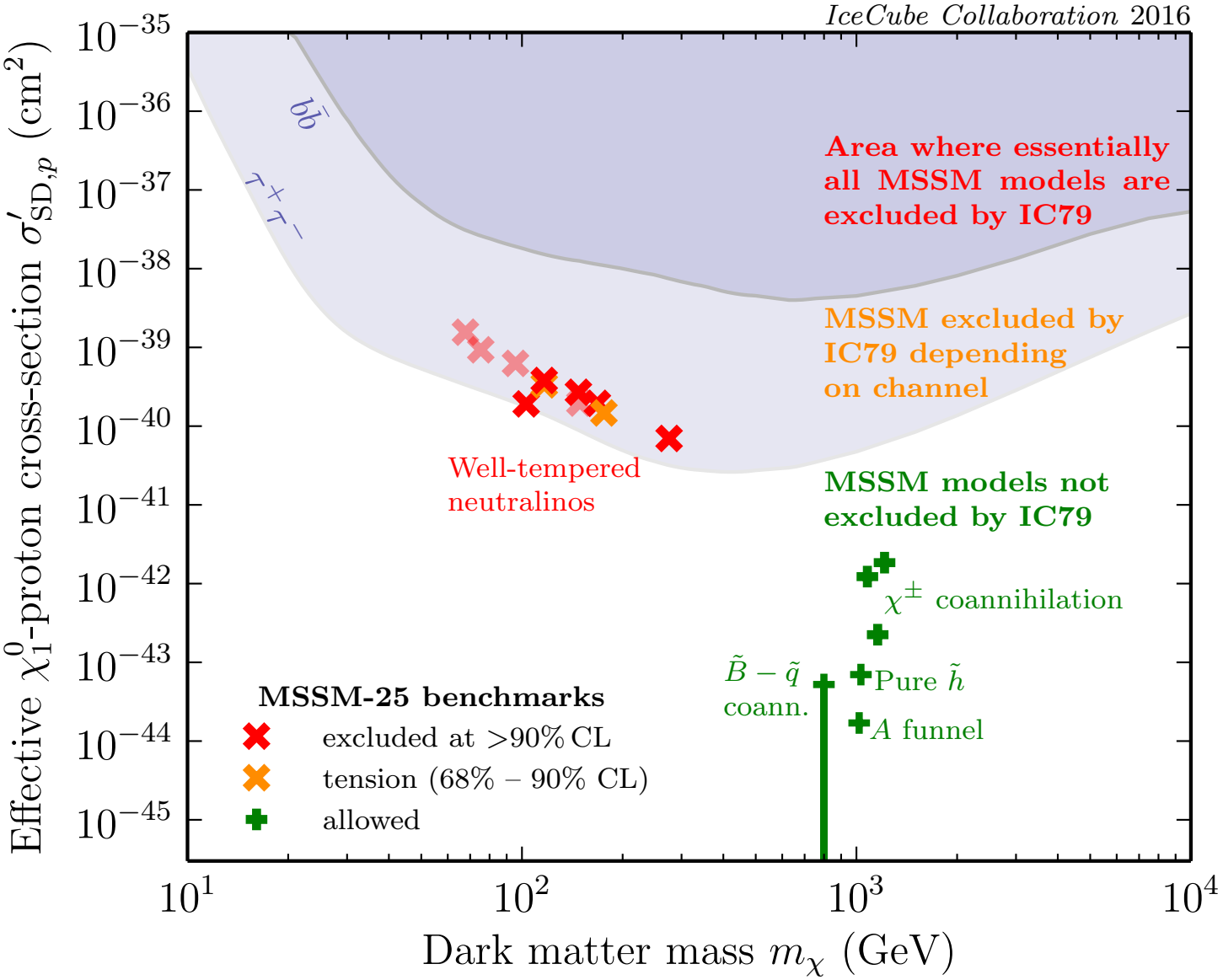
We still can study the model if DM annihilates (partly) into SM particles

- But DM particle X can be light and feebly coupled (t-channel) SHiP

$$\sigma_0 \sim \frac{\xi^4}{M_X^2}$$

  ξ is not a gauge coupling within GUT !
- With small σ_0 one needs entropy production
- σ_0 may be increased by s-channel resonance, $M_Y \approx 2M_X$
- annihilation can be amplified by co-annihilation channels, $X + A \to SM$
- With light messangers between Dark and Visible sectors many estimates change, say $\sigma_0 = \sigma_0(v)$
- DM interaction at freeze-out and now are not the same
  say, Sommerfield enhancement of the annihilation of slow particles $v \sim 10^{-3}$

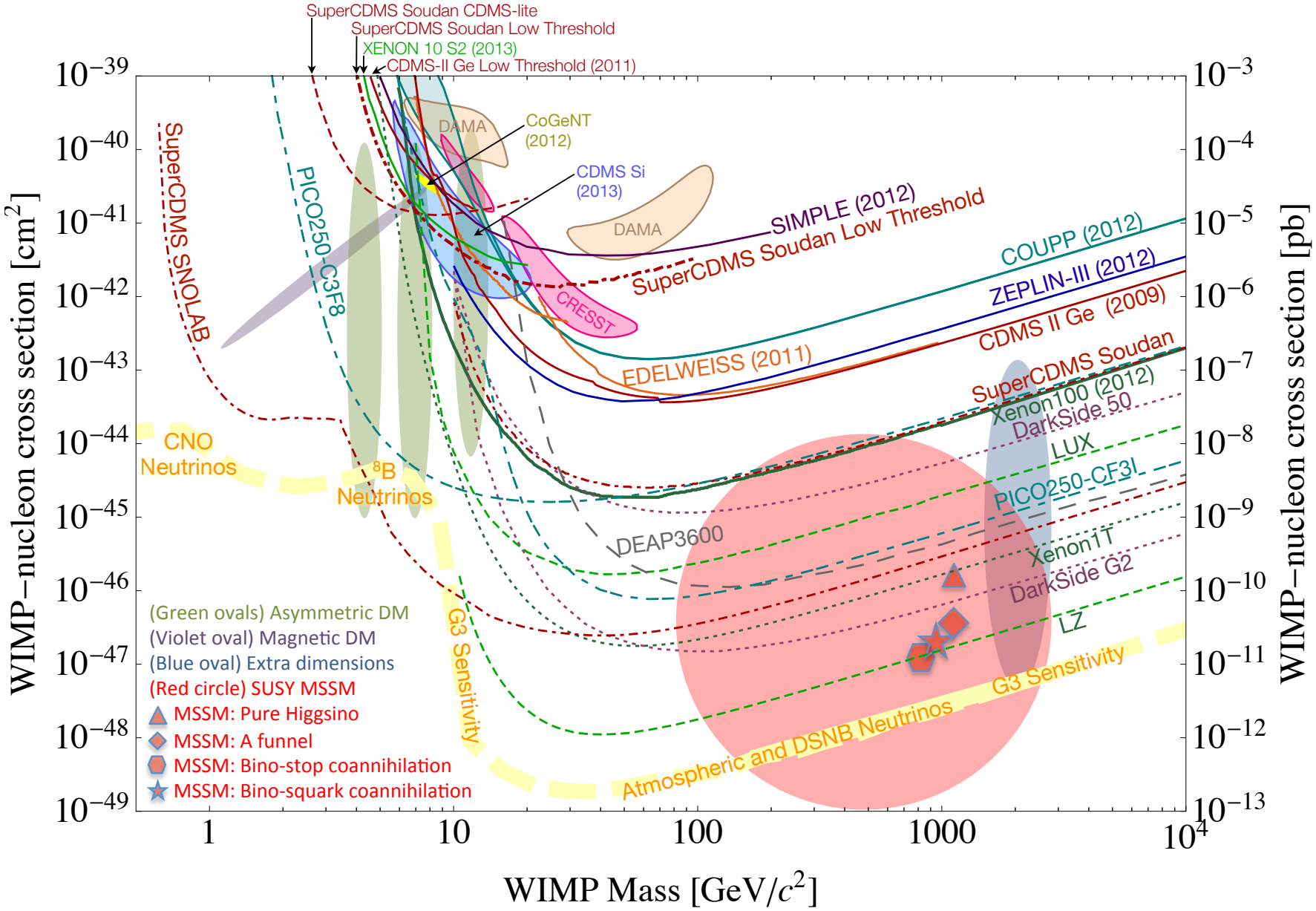
Constraining the DM model parameter space



M.G. Aartsen at al (2016)

Constraining the DM model parameter space

1310.8327



Minimal, but still testable: scalar Dark Matter

$$V_S = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 H^\dagger H$$

$$m_S = \sqrt{\mu_S^2 + \frac{1}{2}\lambda_{hS} v^2}$$

$$\Omega_S \propto m_S n_S \propto \frac{1}{\sigma_{ann}} \propto \frac{m_S^2}{\lambda_{hS}^2}$$

indirect:

$$\text{flux}(SS \to SM) \propto n_S^2 \sigma_{ann} \propto \frac{1}{\lambda_{hS}^2}$$

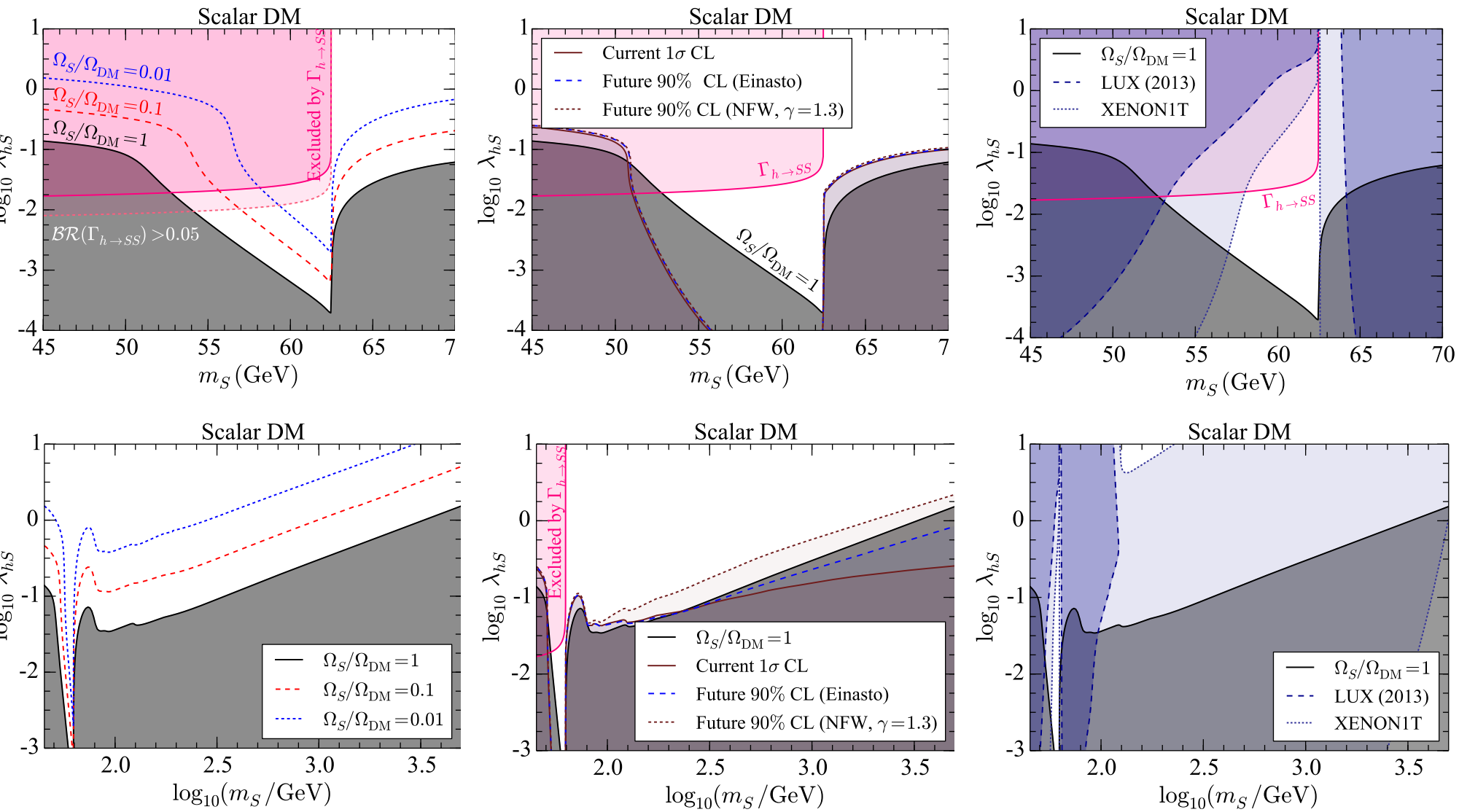
direct:

$$\Gamma(SA \to SA) \propto n_S \sigma_{ann} \propto \frac{1}{m_S}$$

- EW phase transition of I order ?
- EW vacuum stability ?

Constraints on scalar Dark Matter

A.Beniwal et al (2015)



Discussion on WIMPs

Most natural properties:

- to be in equilibrium in primordial plasma up to very freezout (and in kinetic equilibrium even later)
- to form a symmetric component:

$$X = \bar{X} \quad \text{or} \quad n_X = n_{\bar{X}}$$

But what we have in reality?

- We are sure there were
  - Big Bang Nucleosynthesis (starting from 1 MeV)
  - Recombination (at about 0.3 eV)

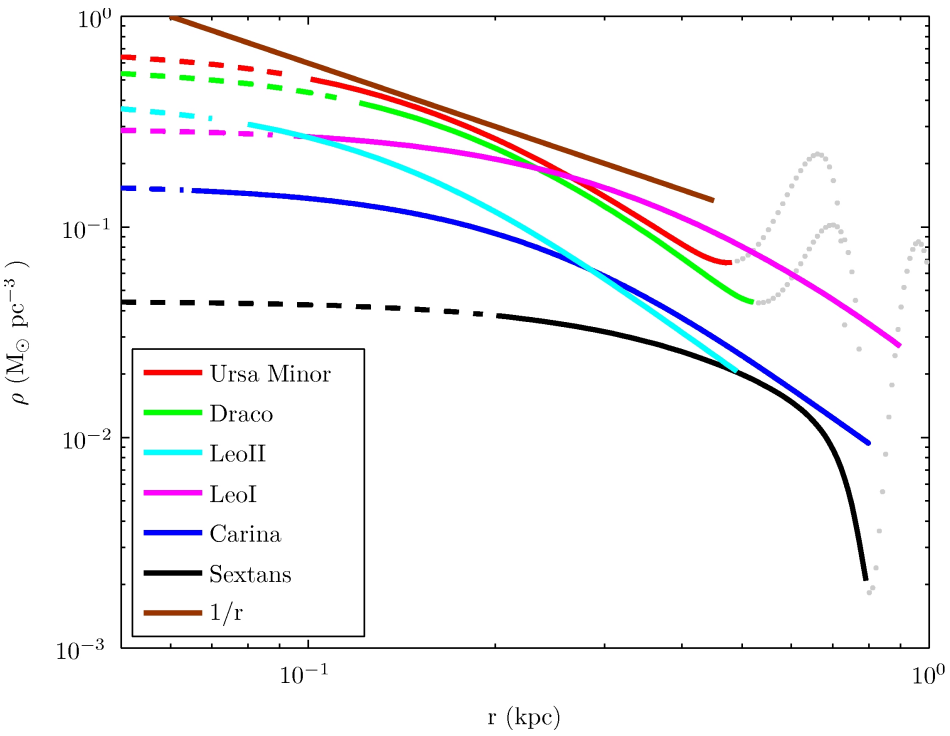
  and both are significantly "out-of-equilibrium" processes
- The visible matter is asymmetric, so that

$$f \neq \bar{f} \quad \text{and} \quad n_f = n_{\bar{f}}$$

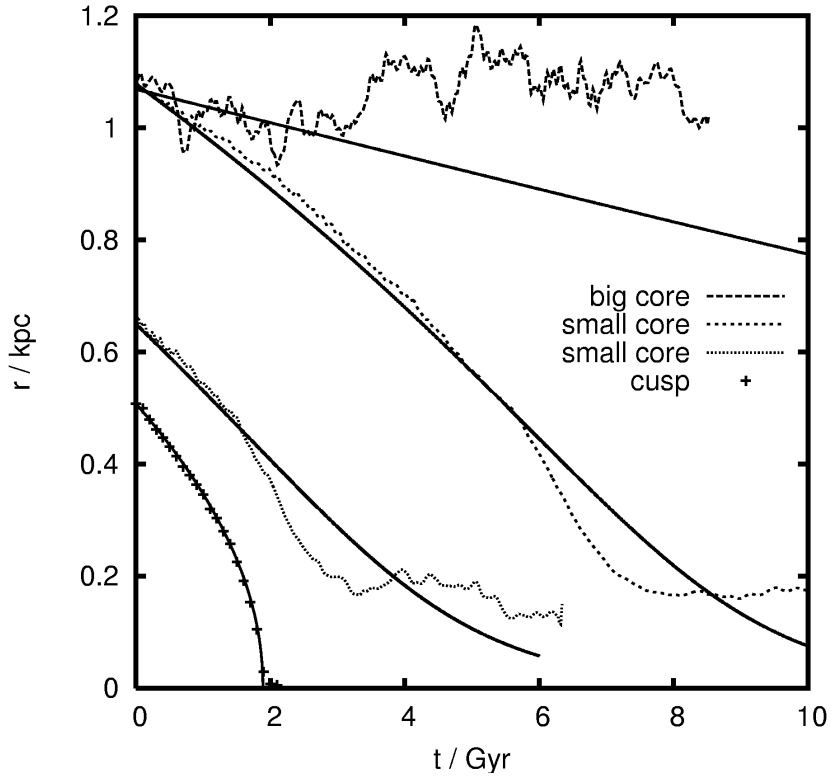
CDM Problems at small-scales ...?

- NFW profile fits nicely DM in galaxy clusters $\rho \propto r^{-1}(r+r_c)^{-2}$
- Dwarf galaxy density profiles: $\rho_M(r) \propto r^{-(0.5-1.5)}$ cusp
  most DM-dominated objects

Cores observed (?)

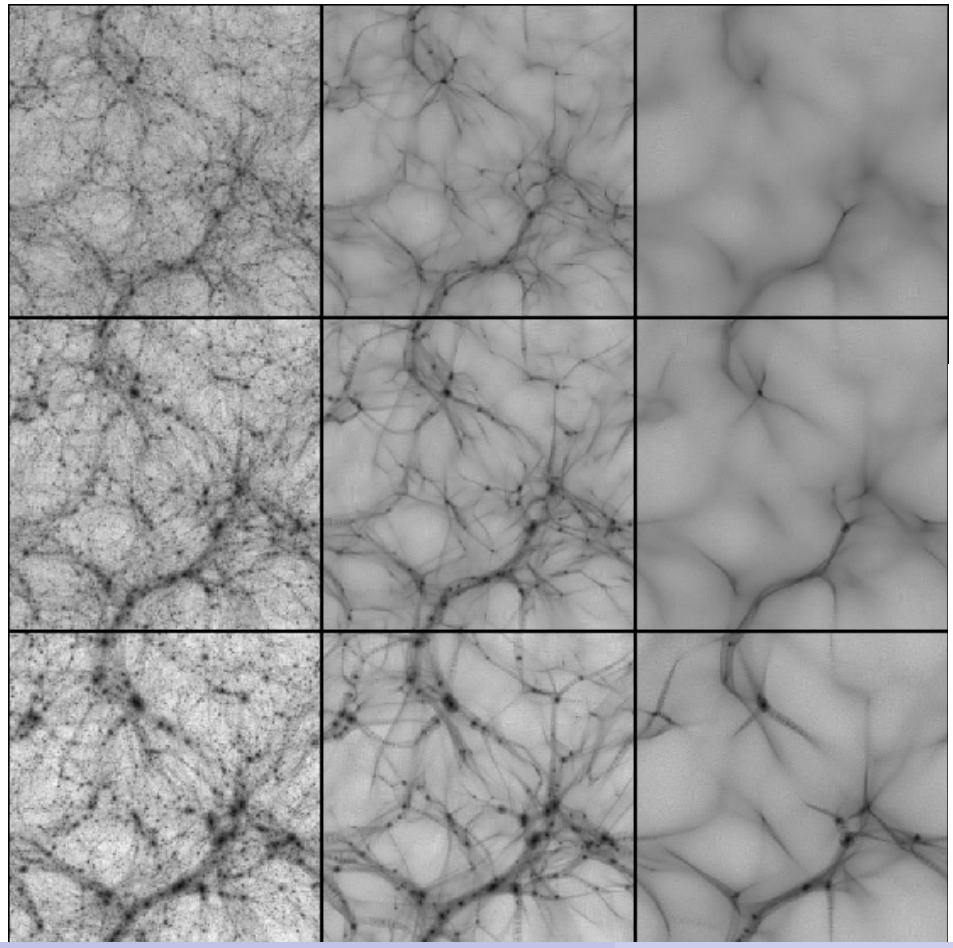


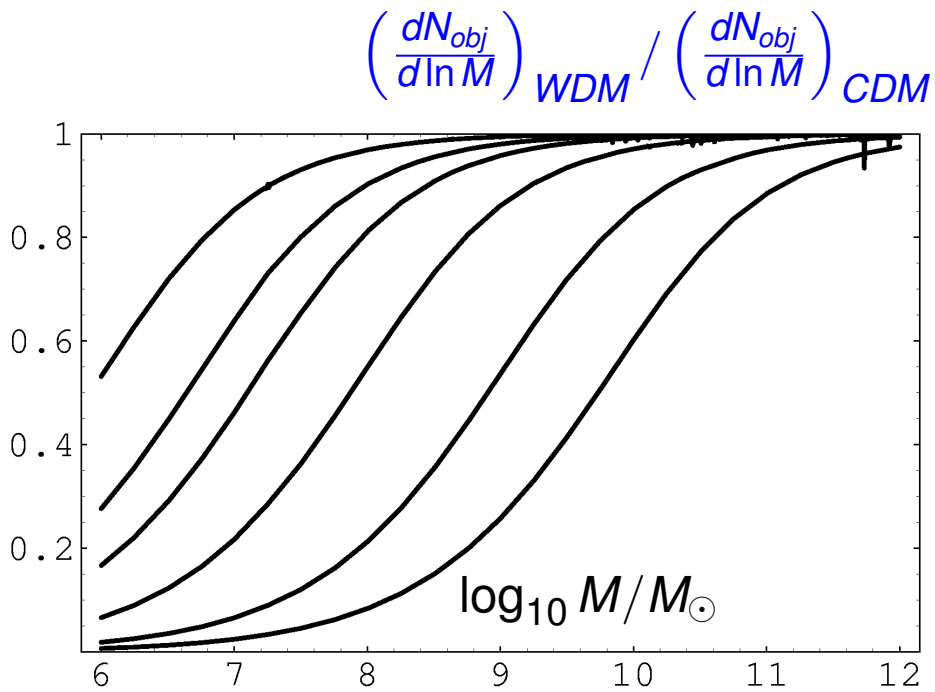
5 Clusters in the Fornax dSph



CDM Problems ...?

- Missing satellites: $\frac{dN_{obj}}{d\ln M} \propto \frac{1}{M}$ no-scale 100 instead of 1000
- "Too big to fail" problem
- Solved (?) by Warm Dark Matter (sterile neutrino, gravitino) free-streaming





Dark Matter: Other well-motivated candidates

Unrelated to the EW scale!

- sterile neutrinos — active neutrino oscillations
- light scalar field — string theory
- axion — strong CP-problem
- gravitino — local SUSY
- Heavy relics — GUTs
- (Topological) defects — GUTs
- Massive Astrophysical Compact Heavy Objects
- Primordial black hole (remnants) — Phase transitions, exotic inflation, reheating

Multicomponent Dark Matter ?

γ, ν, H, He

Dark Matter properties from astrophysics

1. stable on cosmological time-scale
2. (almost) collisionless — to form ellipsoidal halos
3. (almost) electrically neutral — to be Dark
4. stability of globular stellar clusters — $M_X \lesssim 10^3 M_\odot \approx 10^{61}$ GeV
   otherwise too strong tidal forces
5. confinement in a galaxy: — quantum physics!

   de Broglie wavelength: $\lambda = 2\pi/(M_X v_X) < l_{\text{galaxy}}$, — for bosons

   in a galaxy $v_X \sim 0.5 \cdot 10^{-3}$ $\longrightarrow$ $M_X \gtrsim 3 \cdot 10^{-22}$ eV

   for fermions

   Pauli blocking: $M_X \gtrsim 750$ eV

$$f(\mathbf{p},\mathbf{x}) = \frac{\rho_X(\mathbf{x})}{M_X} \cdot \frac{1}{\left(\sqrt{2\pi} M_X v_X\right)^3} \cdot e^{-\frac{\mathbf{p}^2}{2M_X^2 v_X^2}}\Bigg|_{\mathbf{p}=0} \leq \frac{g_X}{(2\pi)^3}$$

Dark Matter: non-thermal production

1. in the primordial plasma of SM particles (via scatterings, oscillations): gravitino; sterile neutrino of 1-50 keV
2. at phase transitions: axion of $10^{-4} - 10^{-7}$ eV; Q-balls; strangelets (?)
3. during inflation: classical scalar
4. at reheating (after inflation?): any guy coupled (only) to inflaton
   - perturbatively: inflaton decays; production by external (inflaton) field
   - non-perturbatively: Bose-enhancement of; coherent production by external field
5. while the Universe expands: gravity produces any particles at $H \sim M_X$

Dark Matter: Other well-motivated candidates

Unrelated to the EW scale!

- sterile neutrinos — sharp line: $\nu_s \to \nu_a + \gamma$, (XMM, INTEGRAL, ...)
- light scalar field — caustics in Bose condensate
- axion — oscillations $a + \mathbf{B} \to \gamma$
- gravitino — missing energy at LHC, ...
- Heavy relics — if unstable: decay into Cosmic rays
- (Topological) defects — lensing of CMB
- Massive Astrophysical Compact Heavy Objects — microlensing
- Primordial black hole (remnants) — Cosmic rays

Axion: Natural but fine-tuned

Theory and Nature:

$$\Delta\mathscr{L} \propto \theta G_{\mu\nu} G_{\lambda\rho} \varepsilon^{\mu\nu\lambda\rho}$$

$$\theta < 10^{-9}$$

nonantropic parameter!

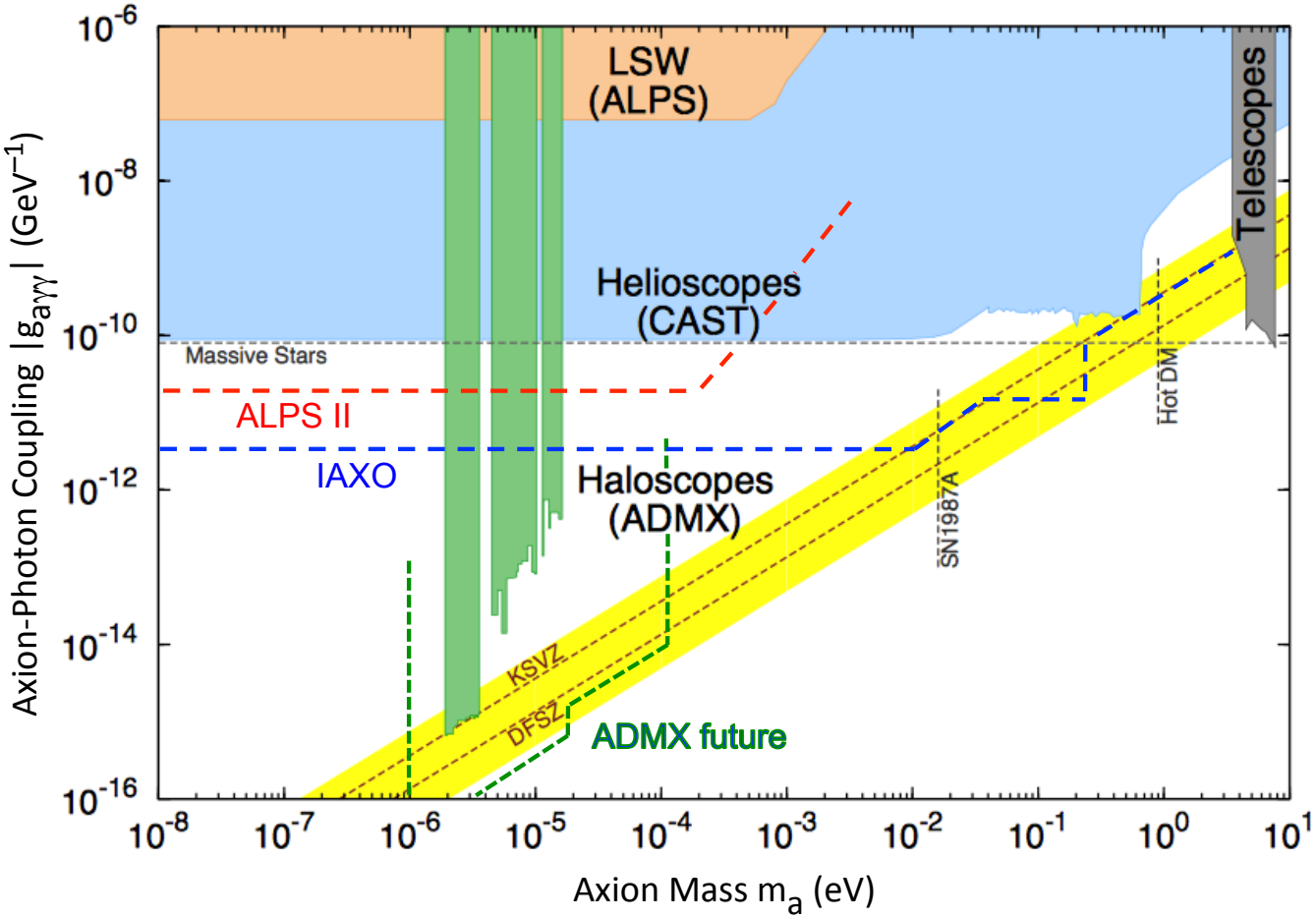
$$\theta \to \theta + a(x)/f_a$$

$$m_{\text{axion}} \simeq f_\pi m_\pi / f_a$$

$$\mathscr{L} \propto g_{a\gamma\gamma} \times a(x) F_{\mu\nu} F^{\mu\nu}$$

Dark Matter region

$$\frac{\Omega_{\text{axion}}}{\Omega_{DM}} = \bar{\theta}_i^2 \cdot \left(\frac{4 \cdot 10^{-6}\,\text{eV}}{m_{\text{axion}}} \right)^{1.2}$$



P.W. Graham et al (2016)

Natural: Sterile neutrino Dark Matter

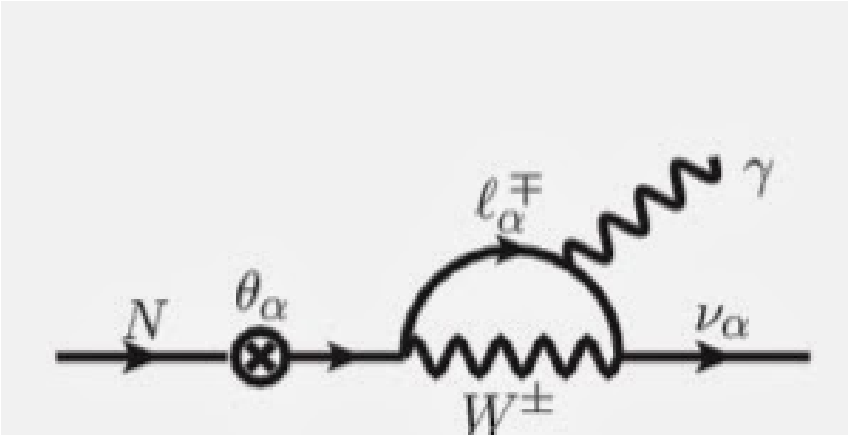
- massive fermions giving mass to active neutrino through mixing

$$m_a \sim \theta^2 m_{sn}$$

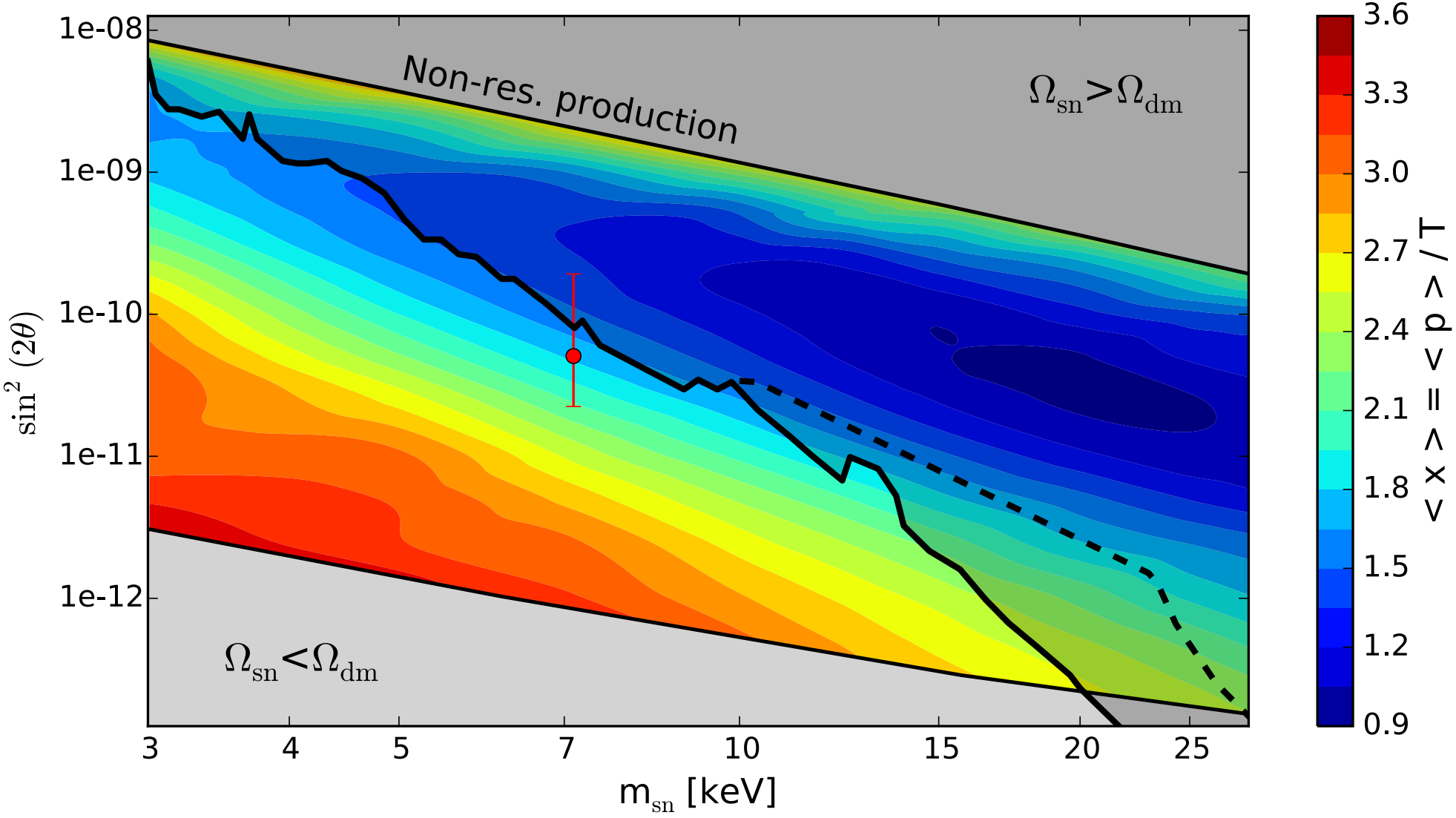
- unstable, but exceeding the age of the Universe at condition

$$\theta^2 < 1.5 \times 10^{-7} \left(\frac{50\,\mathrm{keV}}{m_{sn}} \right)^5$$

- can be searched for because of two-body radiative decay

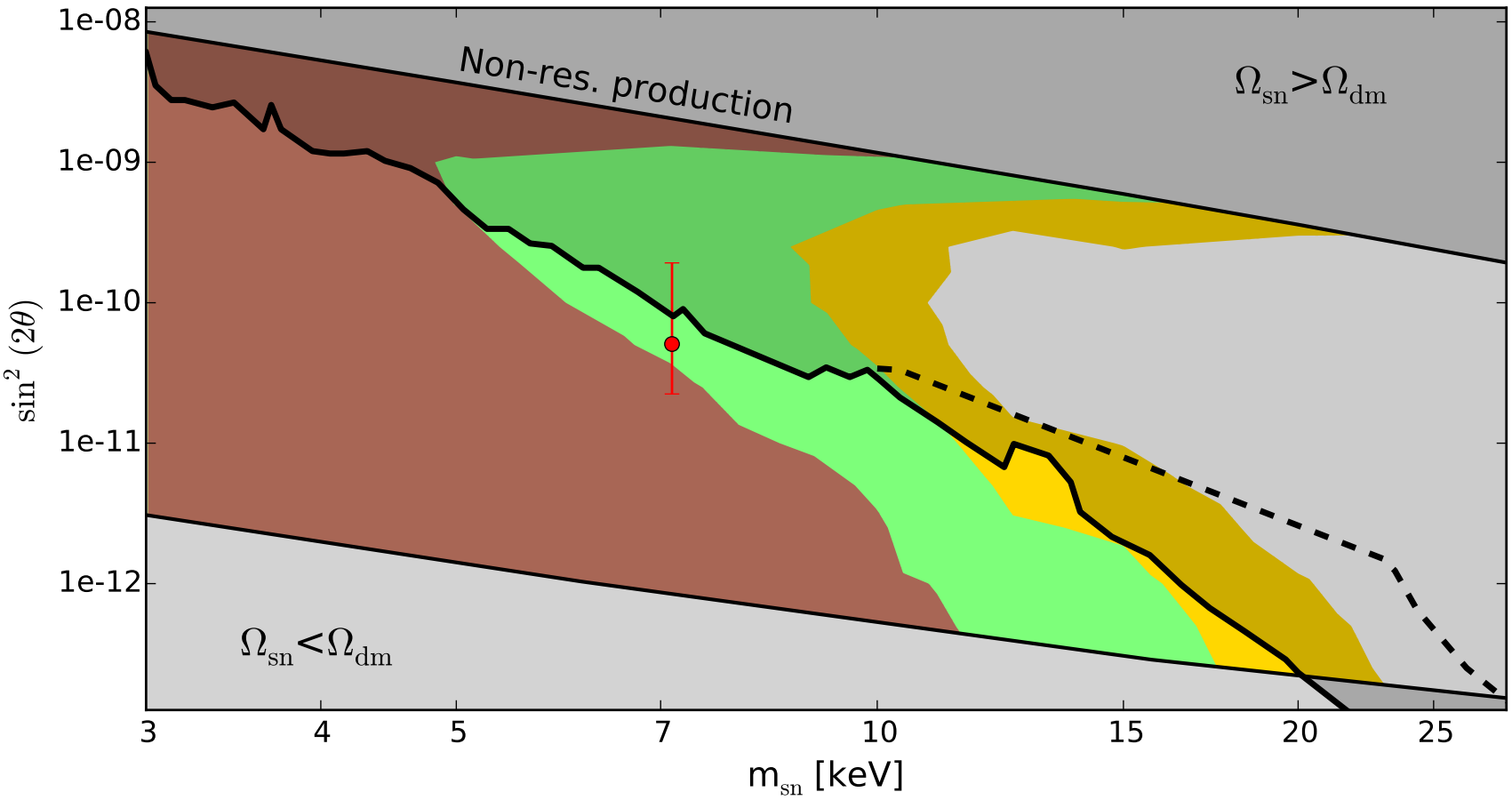


Sterile neutrino Dark Matter



A.Schneider (2016)

Sterile neutrino Dark Matter...



brown: MW satellite counts

green and yellow: Lyman-α

A.Schneider (2016)

Free massive scalar field

$$\mathscr{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\mu \phi - \frac{1}{2} m_\phi^2 \phi^2$$

For the homogeneous scalar field in FLRW expanding Universe

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

we find two-stage evolution:

$$m_\phi < H(t) \quad \Longrightarrow \quad \phi = \phi_i = \text{const}$$

$$m_\phi > H(t) \quad \Longrightarrow \quad p = \langle E_k \rangle - \langle E_p \rangle = 0\,, \quad \rho \sim m_\phi^2 \phi^2 \propto 1/a^3$$

- dust-like substance in the late Universe, $\Omega \propto m_\phi^{1/2} \phi_i^2$
  depends on initial conditions
- presureless at spatial scales $l > 1/m_\phi$ fuzzy DM
- may help (?) with CDM-problems (core-cusp, lack of dwarfs, etc)

Dark Matter: possible guiding principles

Naturality:

- exploit known interactions
  examples: WIMPs, free particles
- part of a well-motivated model
  examples: LSP, axion, sterile neutrinos
- Why $\Omega_B \sim \Omega_{DM}$?
  examples: antibaryonic DM, Mirror World

Minimality:

Use as little new physics as possible

Motivation: No any hints of new physics in experiment

Many models are untestable

example: gravitationally produced free massive fermion

Reality:

Deep insight into the gravitational properties of dark matter

what happen at small scales?

status of: cusp/core in galactic centers, lack of dwarf galaxies, lack of small galaxies

examples: cold dark matter, warm dark matter, selfinteracting dark matter

Examples: both Natural and Minimal

Natural source of dark matter production: gravity

Gravity produces any free massive particle when metric changes in the expanding Universe

most efficiently when $H \sim M$

say, at radiation domination stage

$$\Omega_X \sim \left(\frac{M_X}{10^9\,\mathrm{GeV}}\right)^{5/2}$$

S.Mamaev, V.Mostepanenko, A.Starobinsky (1976)

Modified gravity $(R \to R - R^2/6\mu^2)$

may be responsible for inflation and subsequent reheating

A.Starobinsky (1980)

that is (universal) production of all particles, including those of dark matter

$$\Omega_X \simeq 0.15 \times \left(\frac{M_X}{10^7\,\mathrm{GeV}}\right)^3$$

D.Gorbunov, A.Panin (2010)

Untestable

Observation: why $\rho_B \sim \rho_{DM}$?

1. coincidence

   all well-motivated (hence, natural) models (WIMPs, axions, sterile neutrinos) imply this answer

2. partly coincidence, because:
   - if $\rho_{DM} \ll \rho_B$ then DM is unobservable
     DM can be formed by several specia, only one of which dominates
   - if $\rho_{DM} \gg \rho_B$ then what ?

   (anthropic arguments. . . ?)

3. May be a hint at common origin of dark matter production and baryon asymmetry generation in the early Universe

Dark Matter — messenger — Baryon

Searching for messenger X_a

$$\frac{\lambda_a}{M^2}\,\bar{X}_a d_R \bar{u}^C d_R$$

- If light the best place is a fixed target, e.g. SHiP
- if heavy, the best place is LHC

At LHC the same WIMP-like signature

monojet + missing P_T

$$d + d \to \bar{u} + X\,, \qquad d + u \to \bar{d} + X$$

Other channels for LHC

- BAU is explained by any "neutron-like portal"

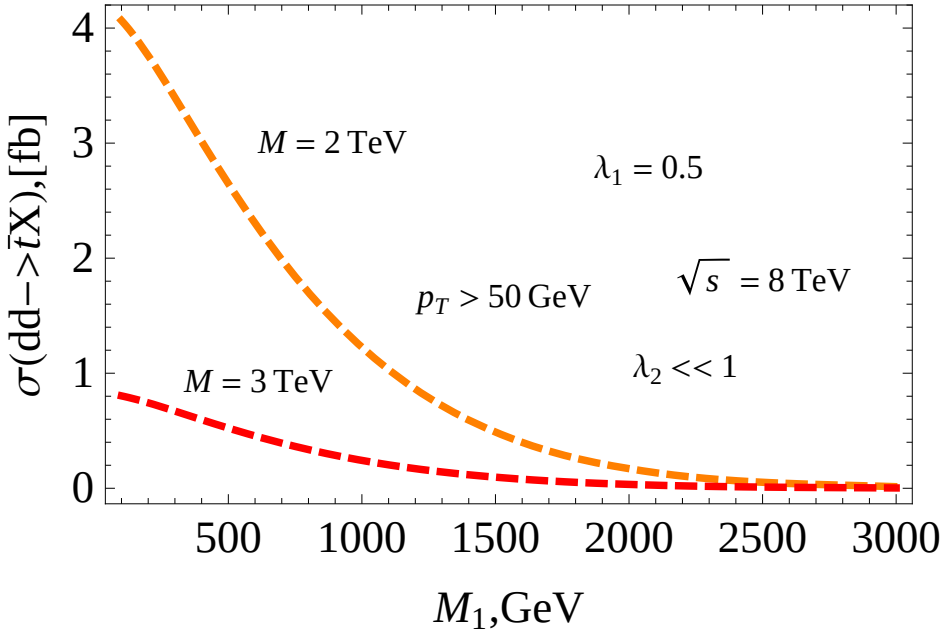
All options must be probed

$$-\mathscr{L}_{\text{int}} = \frac{\lambda_a}{M^2}\bar{X}_a d_R \bar{u}^C d_R$$

$$d = d,\ s,\ b$$

$$u = u,\ c,\ t$$

$$d + d \to \bar{t} + X$$



S. Demidov, D. G., D. Kirpichnikov (2014)

- Searches for $X \to dd\bar{u}$

signatures: jet + 3 jets [forming a particle (invariant mass m^2_{jjj})]
jet + 2 jets + b-jet [. . .]
jet + 2 jets + $\bar{t}$-quark [. . .]
b-jet + . . .
$\bar{t}$-quark + . . .

Conclusions

- We have many Dark Matter models
- Several (and well-motivated, like WIMPs) will be explored at present (e.g. LHC) and forthcoming (e.g. CTA) experiments
- But more model will be invented
- Dark Matter may be multicomponent
- It would be helpful to get more hints from cosmology

DM discovery in a particle physics experiment is not guaranteed !!
But no reasons to give up either

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