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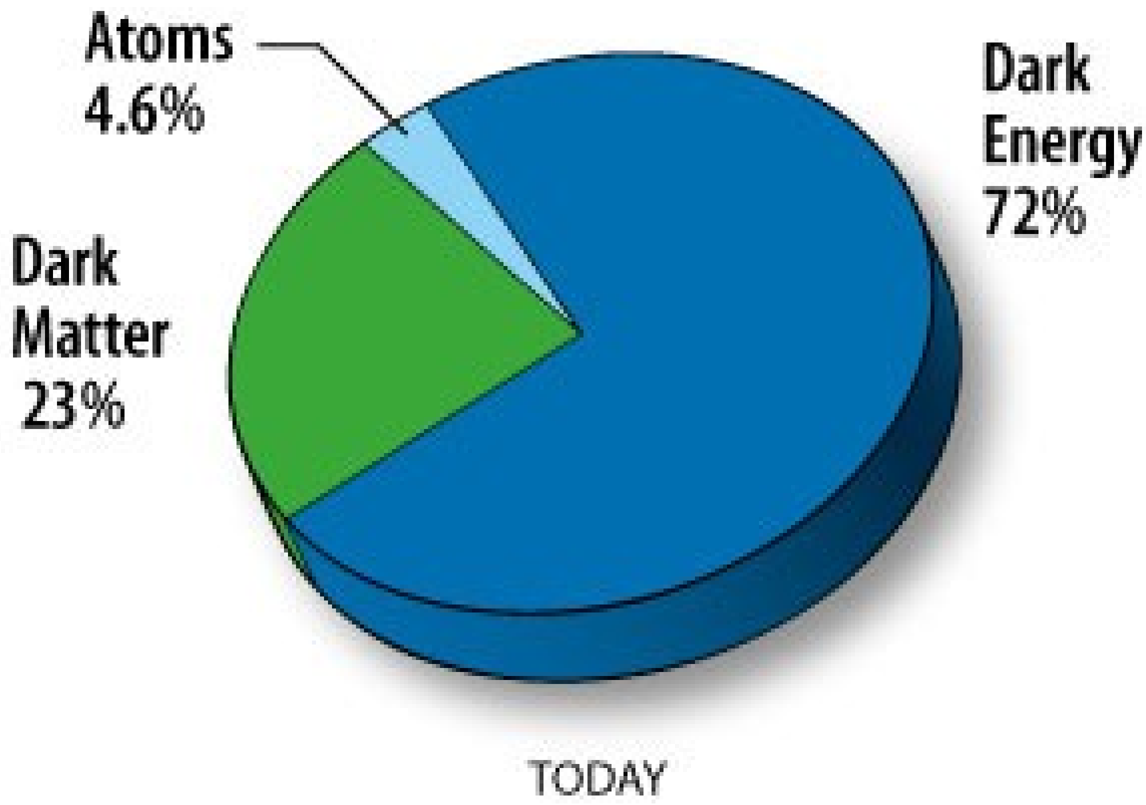
Light dark matter in the Sun

Physun 2012

Lab.Naz. del Gran Sasso
L'Aquila, 08-10 October

The cosmological pie

Non baryonic Dark Matter dominates the matter content of the Universe

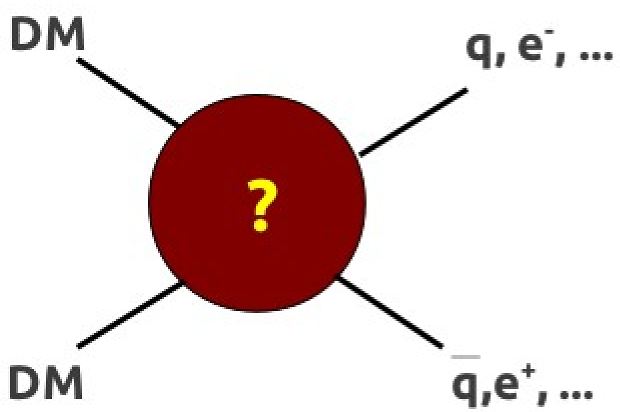


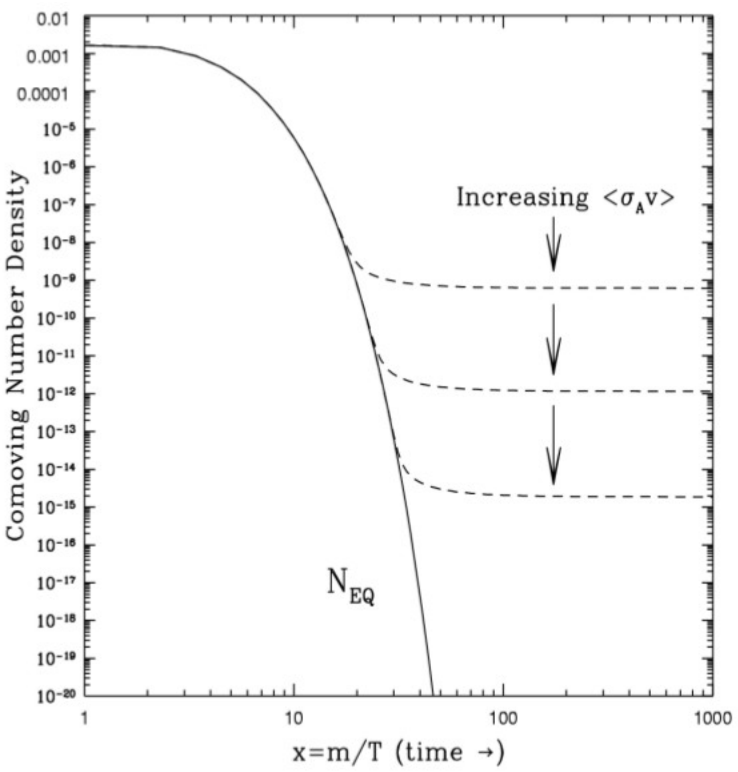
Weakly Interacting Massive Particles

WIMPs paradigma: a simple mechanism to explain present DM density.

DM particles in thermodynamic equilibrium with the plasma at early times

Decoupling when annihilation rate < Hubble expansion rate

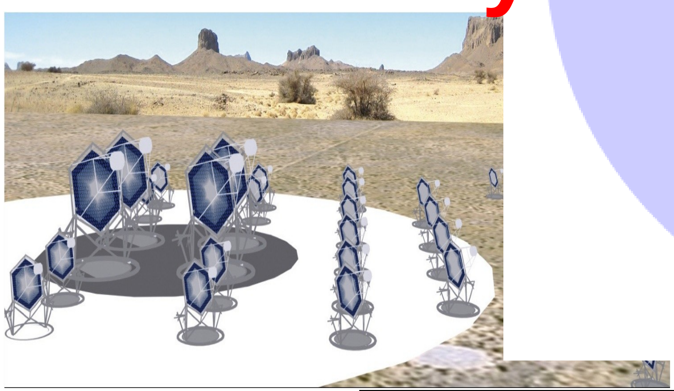




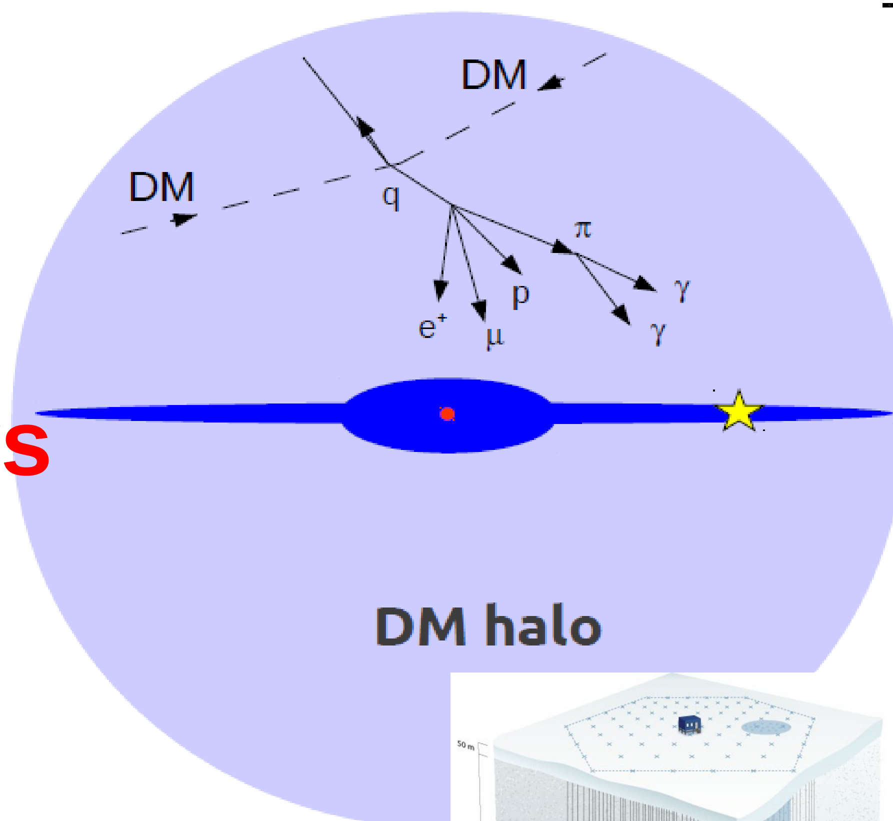
$$\Omega_{WIMP} \approx 0.1 \times \frac{3\ 10^{-26}\ \mathrm{cm}^3 s^{-1}}{\langle \sigma v \rangle}$$

Search for DM with astrophysical observations

Gamma- rays

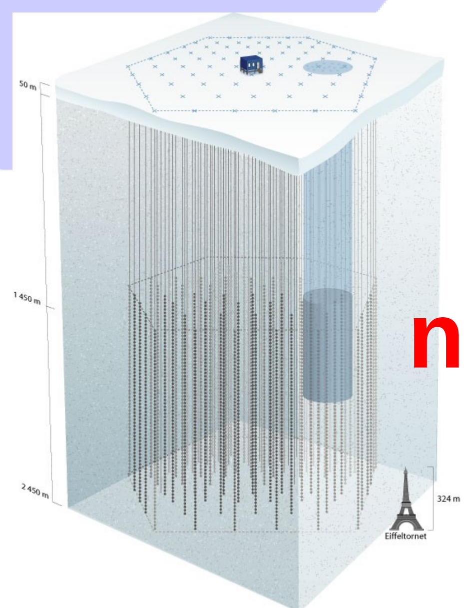


X- rays



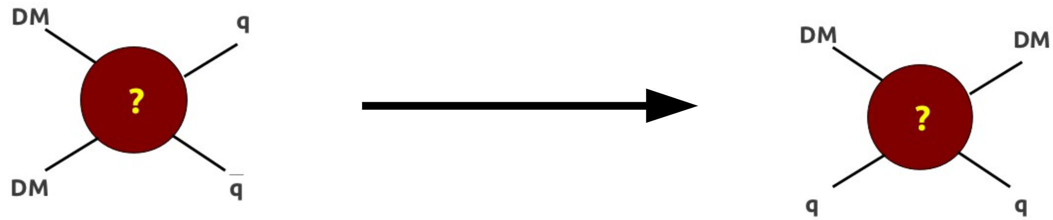
Microwave

Radio



neutrinos

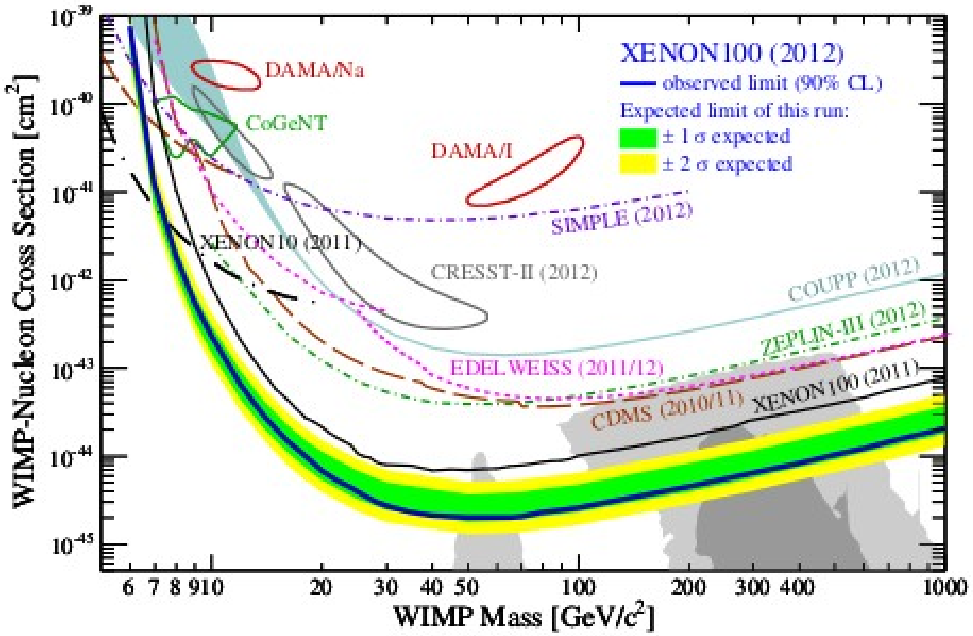
Direct dark matter searches



Impressive progress during last few years!

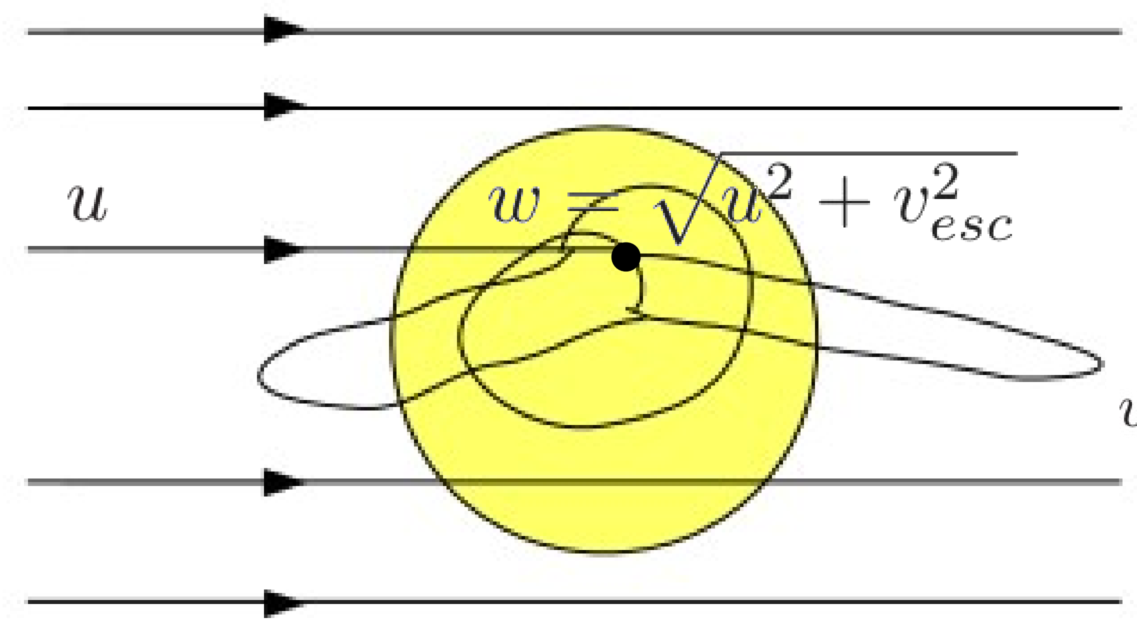
Bounds on the parameter space of theoretical models +

few anomalies DAMA, CoGent, CRESST-II



XENON 2012

Capture of DM in the Sun



$$\frac{dC_i}{dV} = \int_0^{u_{max}} du f(u)\, w\Omega_{v,i}(w)$$

$$w\Omega_{v,i}(w) \propto \sigma_{\chi,i} n_i(r)\, P(w' < v_{esc})$$

Low velocity WIMPs are easy to capture

<u>Astro uncertainties</u>: local DM density + velocity distribution + Sun composition

<u>Particle-Physics uncertainties</u>: DM mass, size and type of interaction,

nuclear Form-factors

Capture of DM in the Sun

Evolution of number of WIMPs in the Sun:

$$\frac{dN_\chi}{dt} = C - C_A N_\chi^2 - C_E N_\chi$$

$$\frac{1}{2} C_A N_\chi^2 = \frac{1}{2} C \tanh^2\left(\frac{t}{\tau_A}\right) \qquad \tau_A = \frac{1}{C C_A}$$

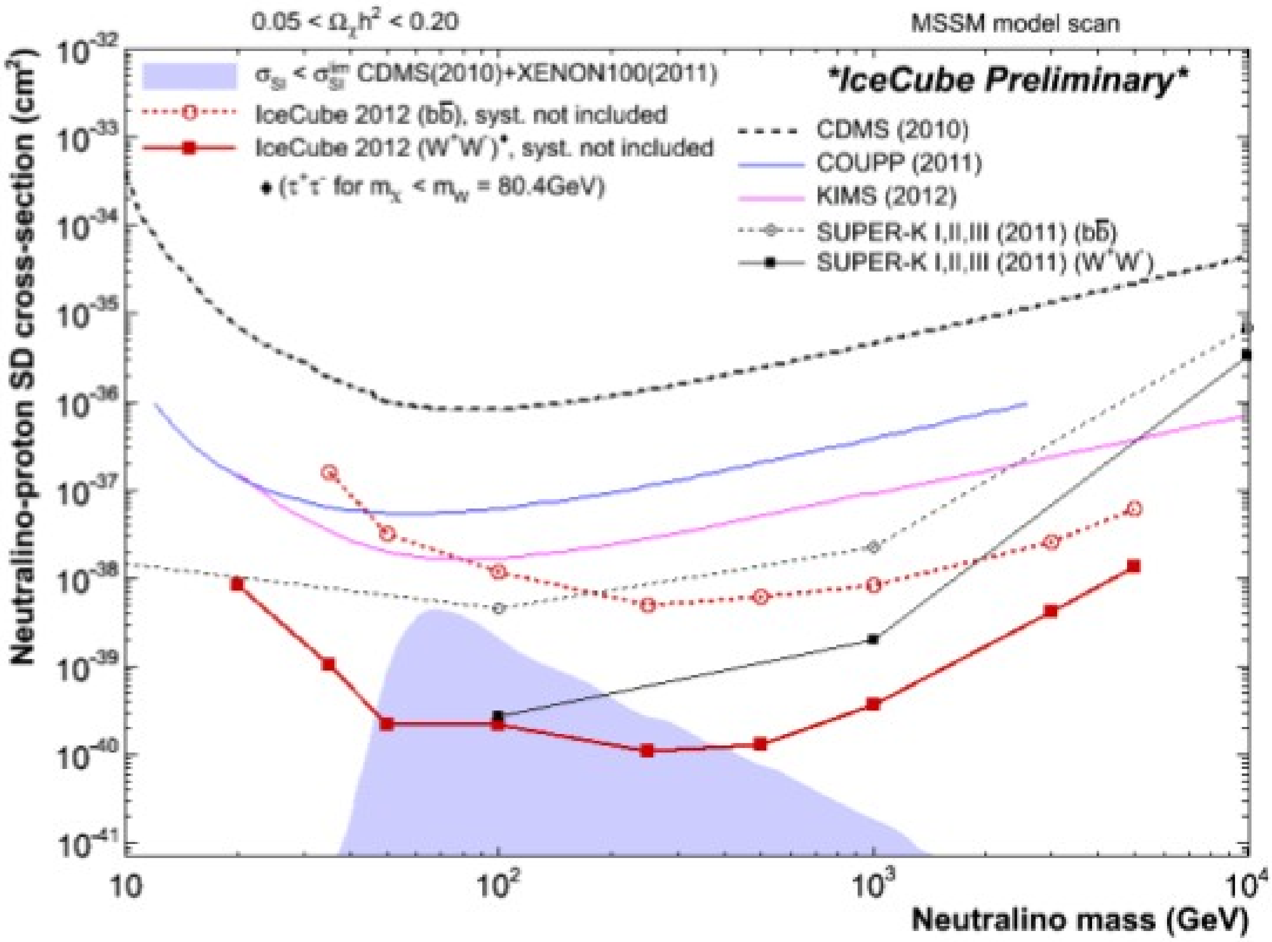
Evaporation is negligible for DM masses below 4-5 GeV

Equilibrium between capture and annihilations if τ_A << age of the Sun

Once the equilibrium is reached annihilation flux depends only on the capture rate

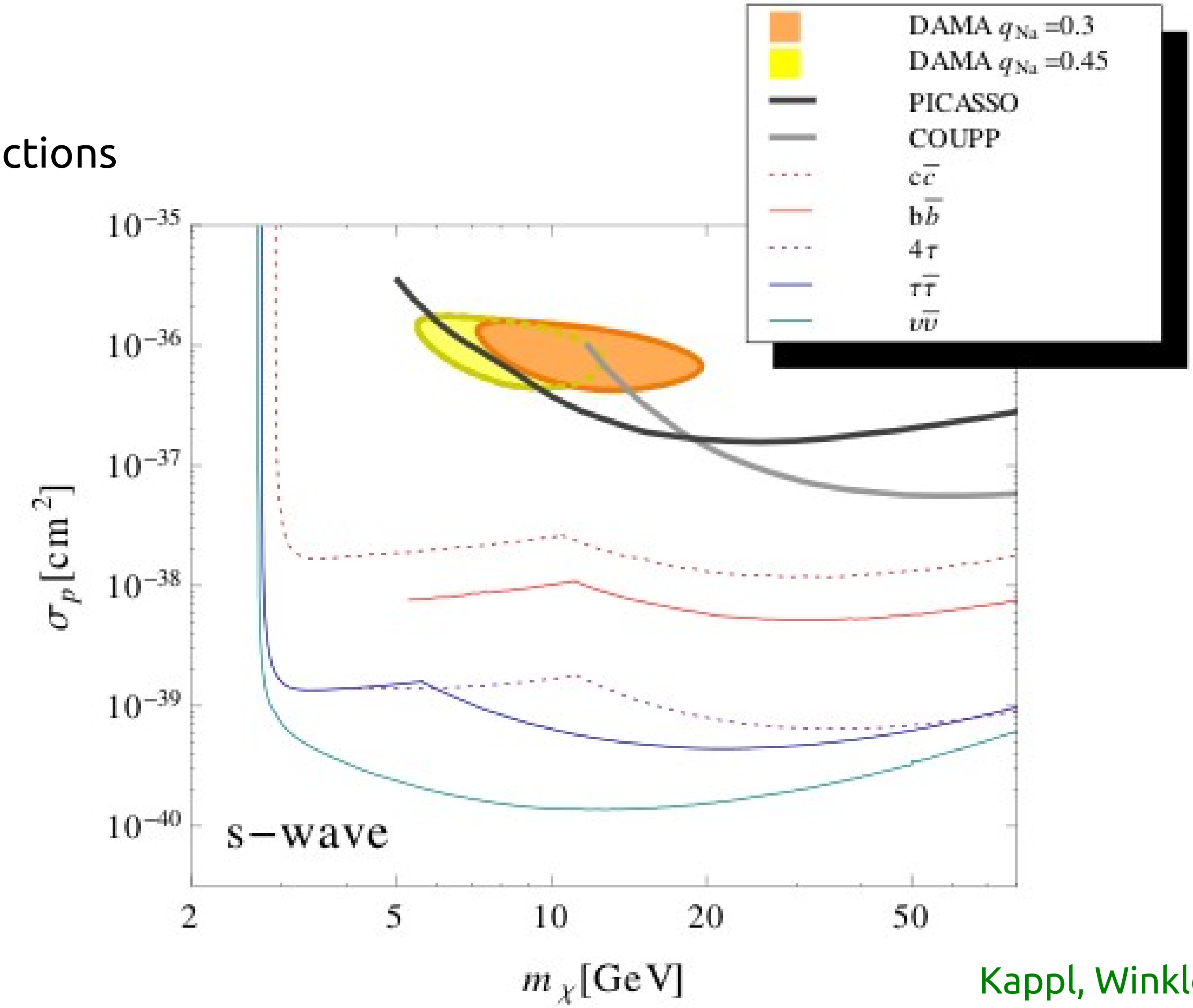
Neutrinos from DM annihilations

Limits are competitive with direct searches for SD interactions



Bounds from SK

SD interactions



Kappl, Winkler 2011

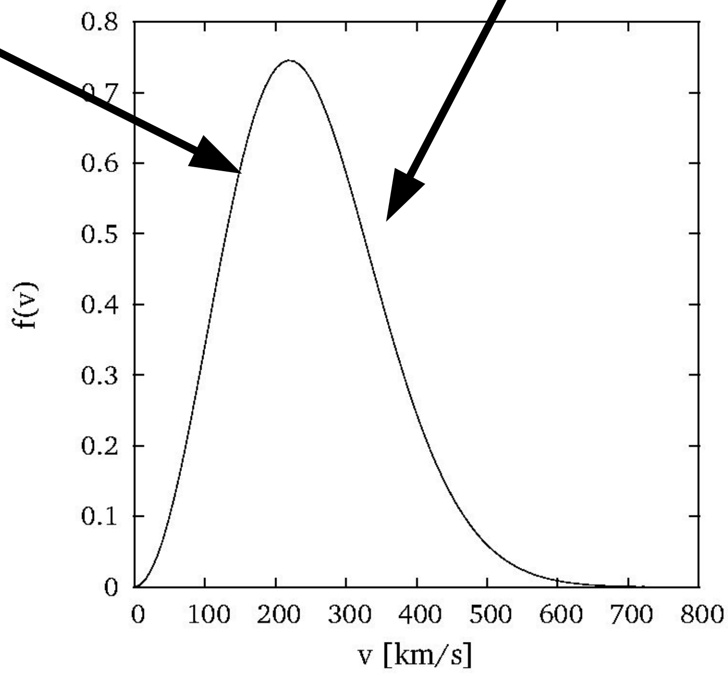
Velocity distribution

Capture in the Sun

probes low-velocities

Direct detection

probes high velocity tail



Departure from a Maxwellian distribution is observed in N-body simulations

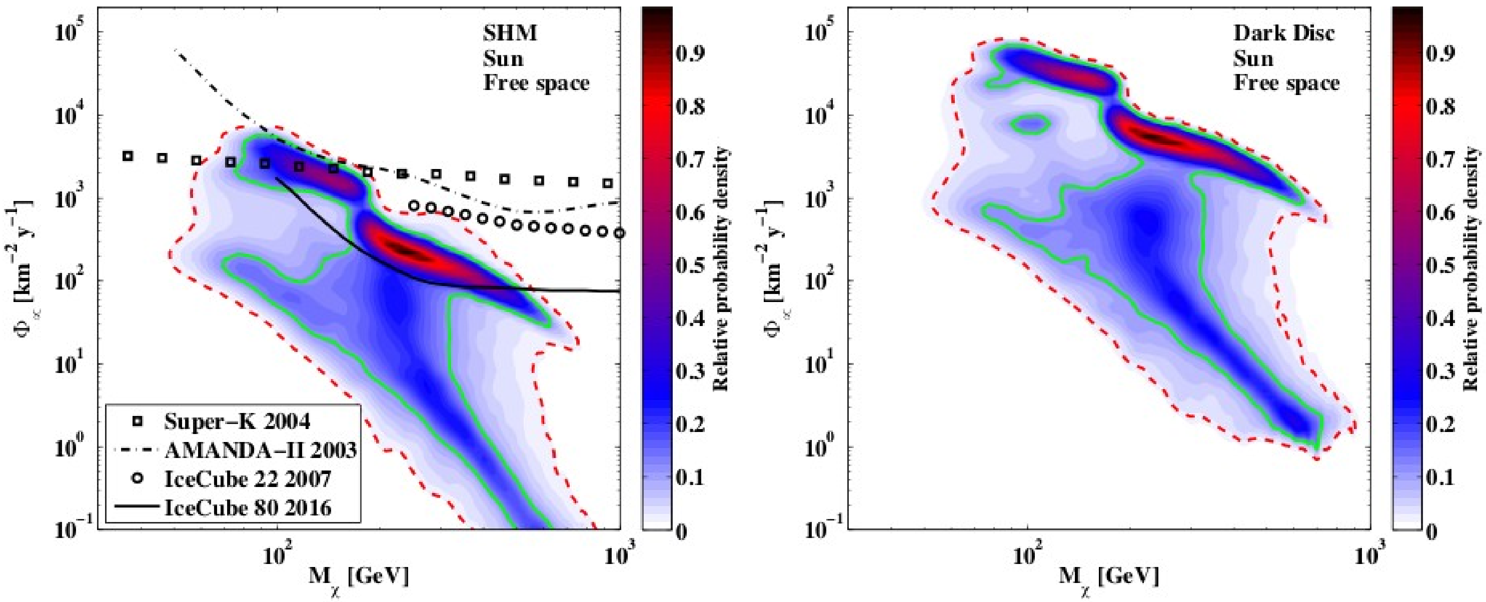
Dark disk

Some N-body simulations finds a Dark disk co-rotating with the star

This implies DM particles move slowly and so are easier to capture

Dark disk could boost the Capture rate up to a factor 10

Small effect for Direct detection

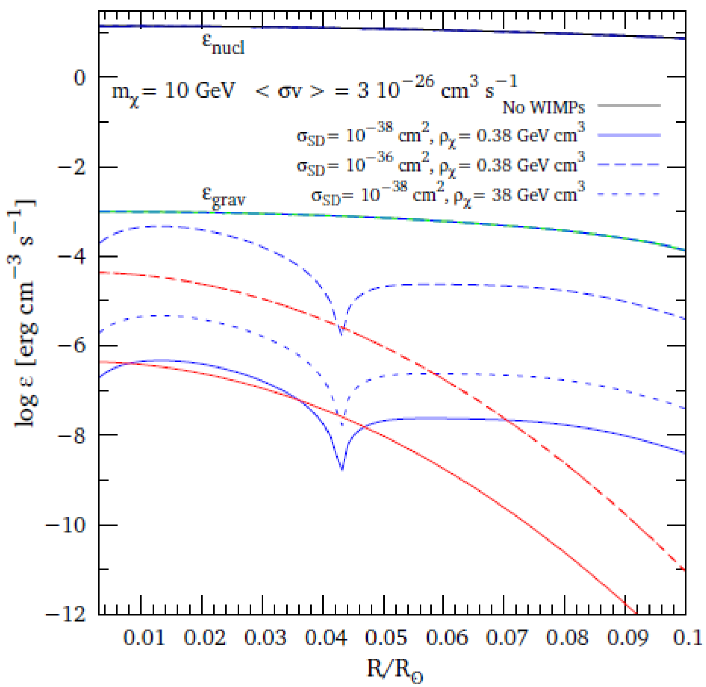


Bruch et al. 2009

Effects on solar structure

“Standard” WIMPs do not affect the structure of the Sun

Energy injected by WIMPs annihilations is very small



This is not true for stars in high DM density environments

e.g. galactic center, first stars. Evolution of these stars is changed

Fairbairn et al. 2008, Taoso et al. 2008, Scott et al. 2008, Freese et al. 2008, Casanellas 2009,...

Feebly annihilating DM

$$\frac{dN_\chi}{dt} = C - C_A N_\chi^2 - C_E N_\chi$$

Large number of DM can sink inside the Sun for small annihilation rates

Equilibrium is not reached for suppressed annihilations cross-sections

Considering $\sigma_p > 10^{-36}$ cm^2 non-equilibrium for $\sigma v < 10^{-33}$ cm^3/s

WIMPs suppressed annihilations for p-wave cross-sections

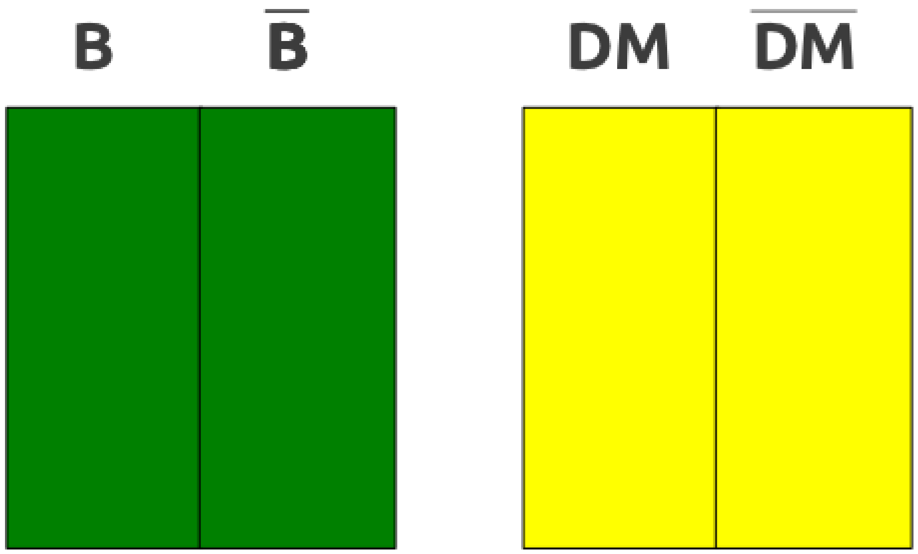
$$\langle \sigma v \rangle = a + bv^2 + \mathcal{O}(v^4) \quad \text{for p-wave annihilations:} \;\; \langle \sigma v \rangle = bv^2$$

$$\text{velocity @ freeze-out } v \sim 0.2c \quad \text{present halo velocity } v \sim 10^{-3}c$$

Asymmetric Dark Matter

We know there is an asymmetry between baryons and anti-baryons

DM sector could be similar.

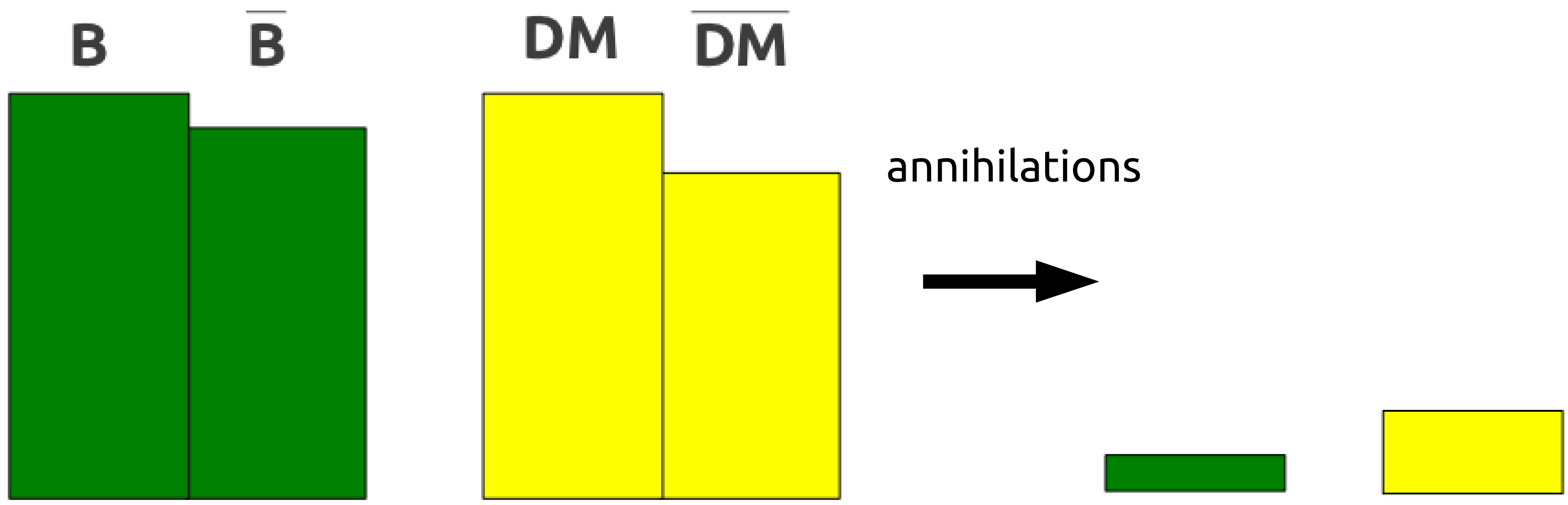


ADM ingredients

DM is different from anti-DM. DM number is violated (like baryon number in SM)

Some mechanism produces an asymmetry in the DM sector

The symmetric part is depleted by annihilations



ADM phenomenology

DM abundance is set by the initial asymmetry

If DM and Baryon asymmetries are similar

$$\frac{\Omega_{DM}}{\Omega_b} = \frac{M_{DM}}{M_b}\frac{n_{DM}}{n_b} \sim 5 \qquad M_{DM} \sim 5M_p \sim 5\ \mathrm{GeV}$$

Nussinov 1985

No DM annihilations because anti-DM is no longer present

Traditional Indirect detection methods do not work

Accumulations in stars is a possibility to test this scenario!

WHAT DM DOES INSIDE THE SUN

DM scatter off nuclei and transport energy inside the star

Two regimes depending on the mean free-path

$$\frac{1}{l_\chi(r)} = \sum_i \sigma_i X_i(r) \frac{\rho(r)}{m_i}$$

- Knudsen regime (large m.f.p.) energy transport from hot to cool regions
- ↓ Increasing scattering cross-section (and so capture rate)

Conduction (small m.f.p.) energy transport is local

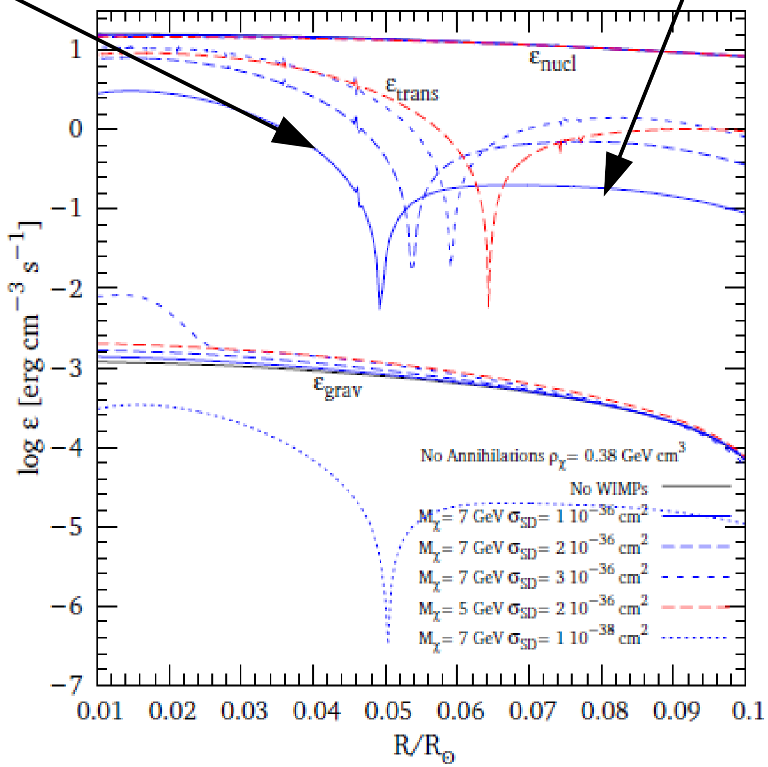
For reference $l_\chi(0) \sim 10^{10}$ cm $\sim 0.15 R_\odot$ for $\sigma_{SD} = 10^{-36}\text{cm}^2$

See Gould, Raffelt 1990, Spergel, Press1985

Energy transport inside the Sun

DM takes away energy

DM deposits energy

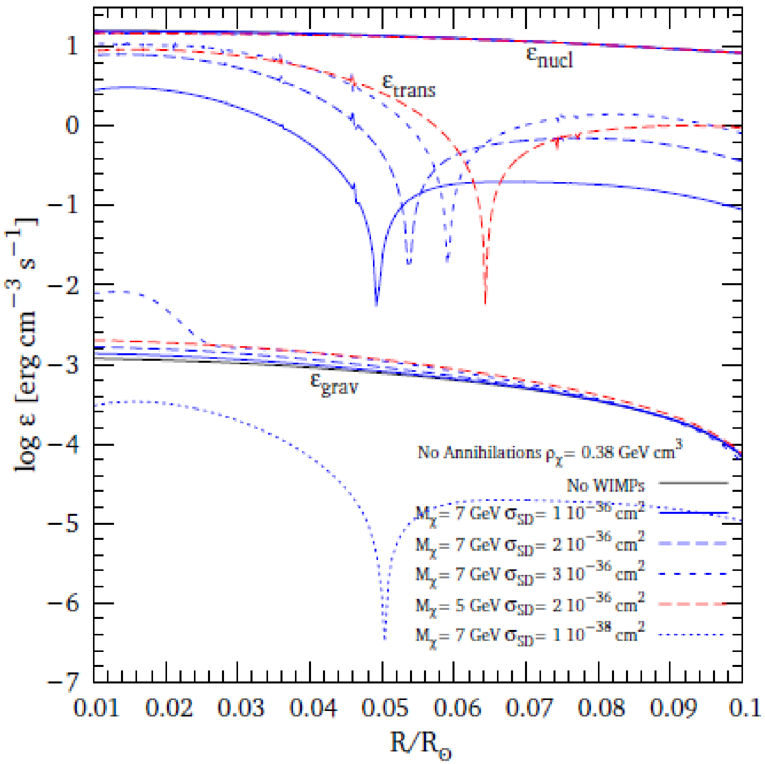


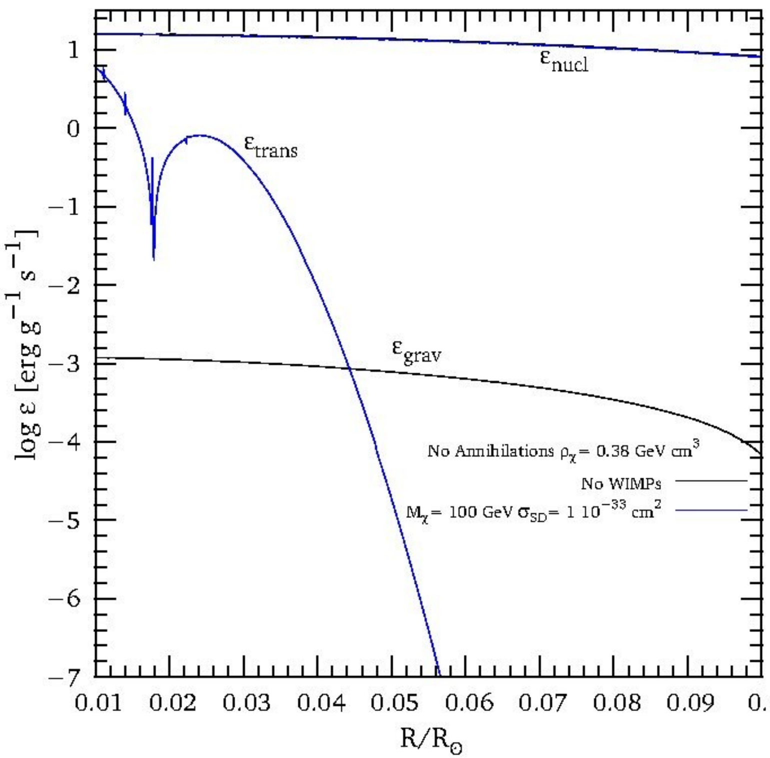
Energy transported by DM can be of the order of the nuclear energy

Energy transport inside the Sun

For large masses DM confined at small radii: transport is inefficient

$$n_\chi(r) = n_0 e^{-(m_\chi \phi(r))/T_\chi}$$

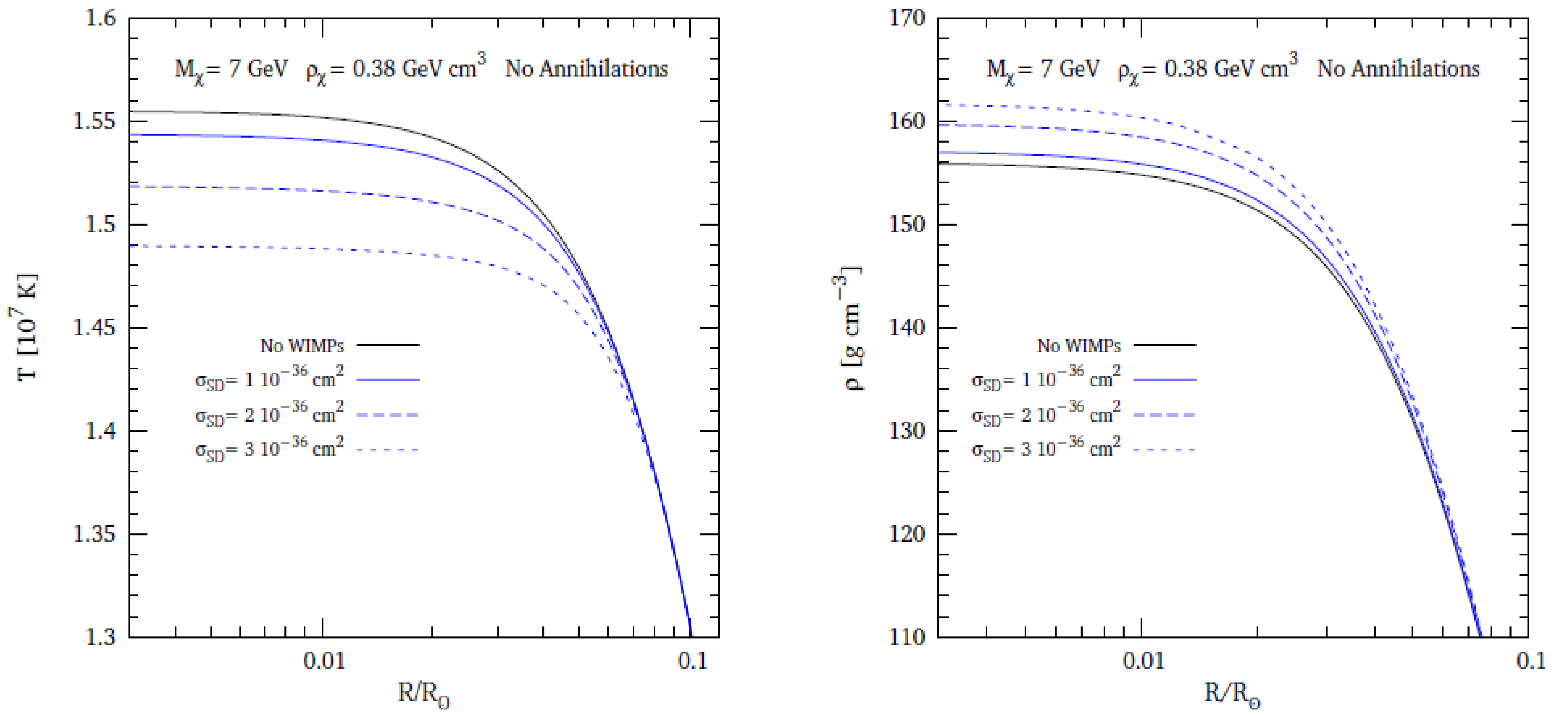




Effects on stellar structure

DM extract energy from the center decreasing the temperature

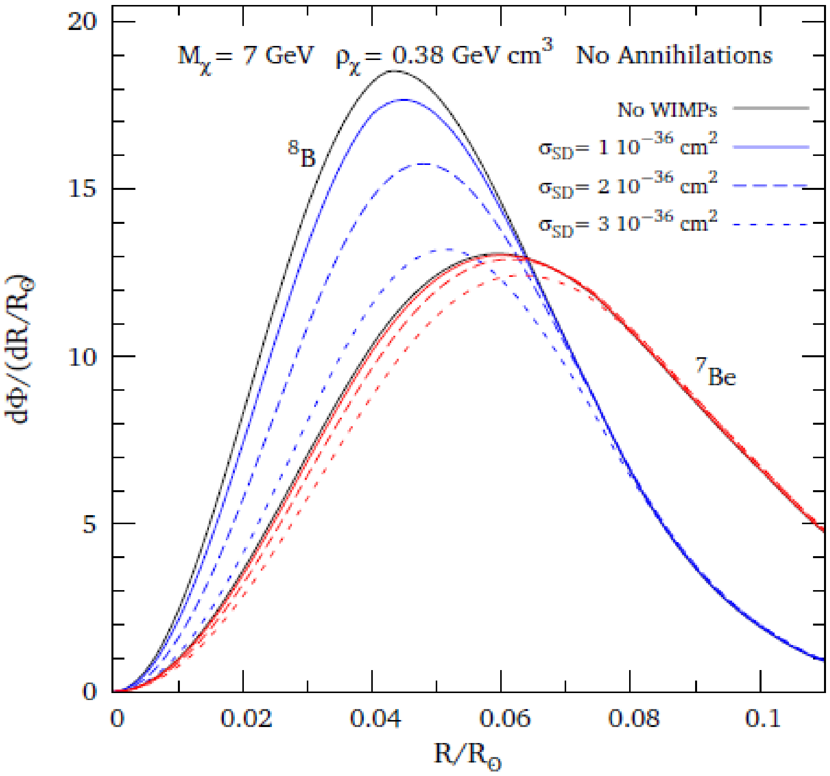
The core contracts so the central density is increased



Solar neutrinos: a diagnostic tool

B8 neutrinos flux is reduced

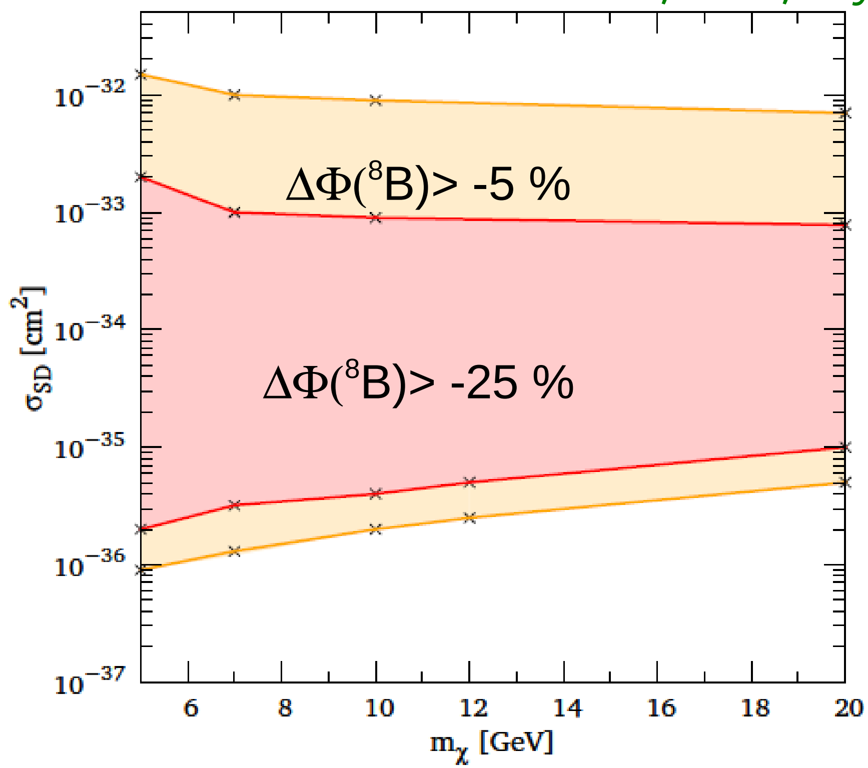
Be7 less sensitive because produced at larger radii



Constraints on DM

DM implemented in GENEVA code

MT, Iocco,Meynet, Bertone, Eggenberg 2010



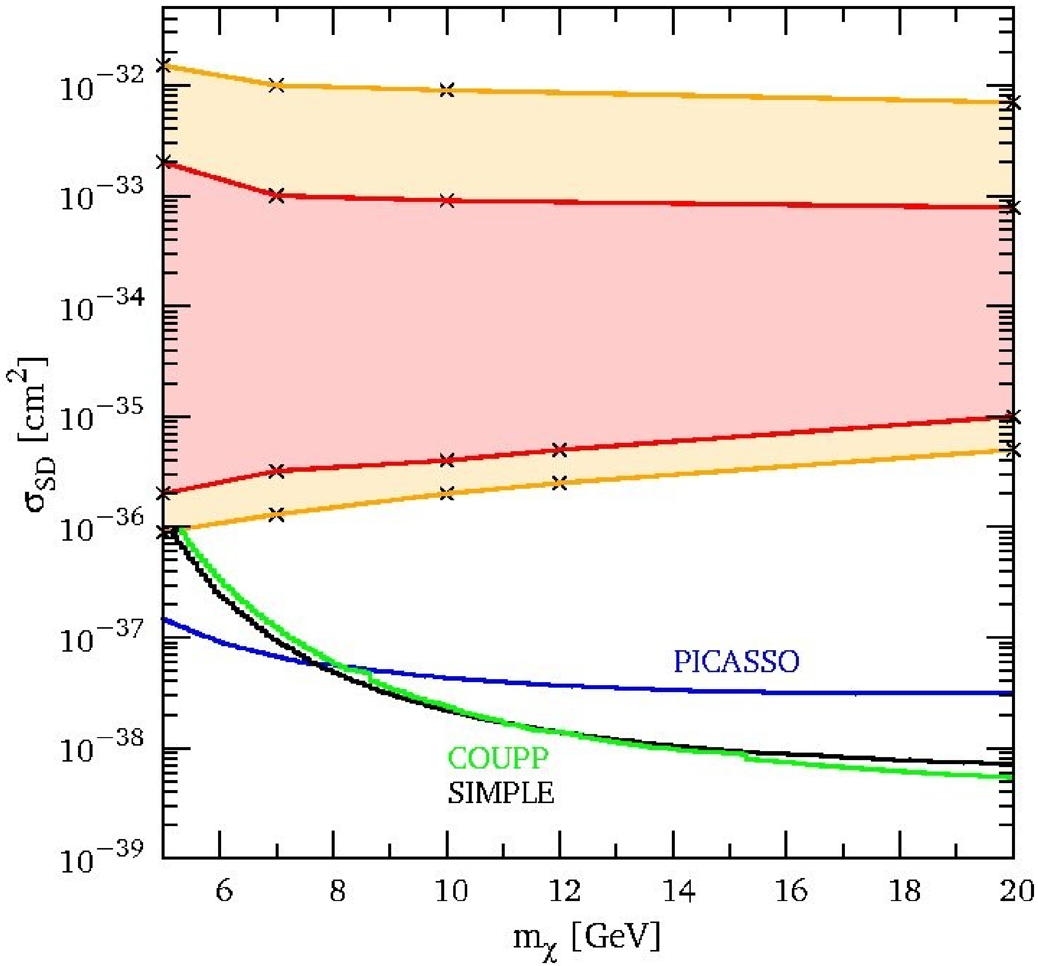
No effects for masses < 4 GeV because of evaporation $E_\odot \sim \frac{1}{t_\odot} e^{-30\,(m_\chi - m_{\rm evap})/m_{\rm evap}}$

At large cross-sections transport is local and so very inefficient

See also Bottino et al. 2002, Frandsen et al. 2010, Cumberbatch et al 2010, Lopes et al. 2012

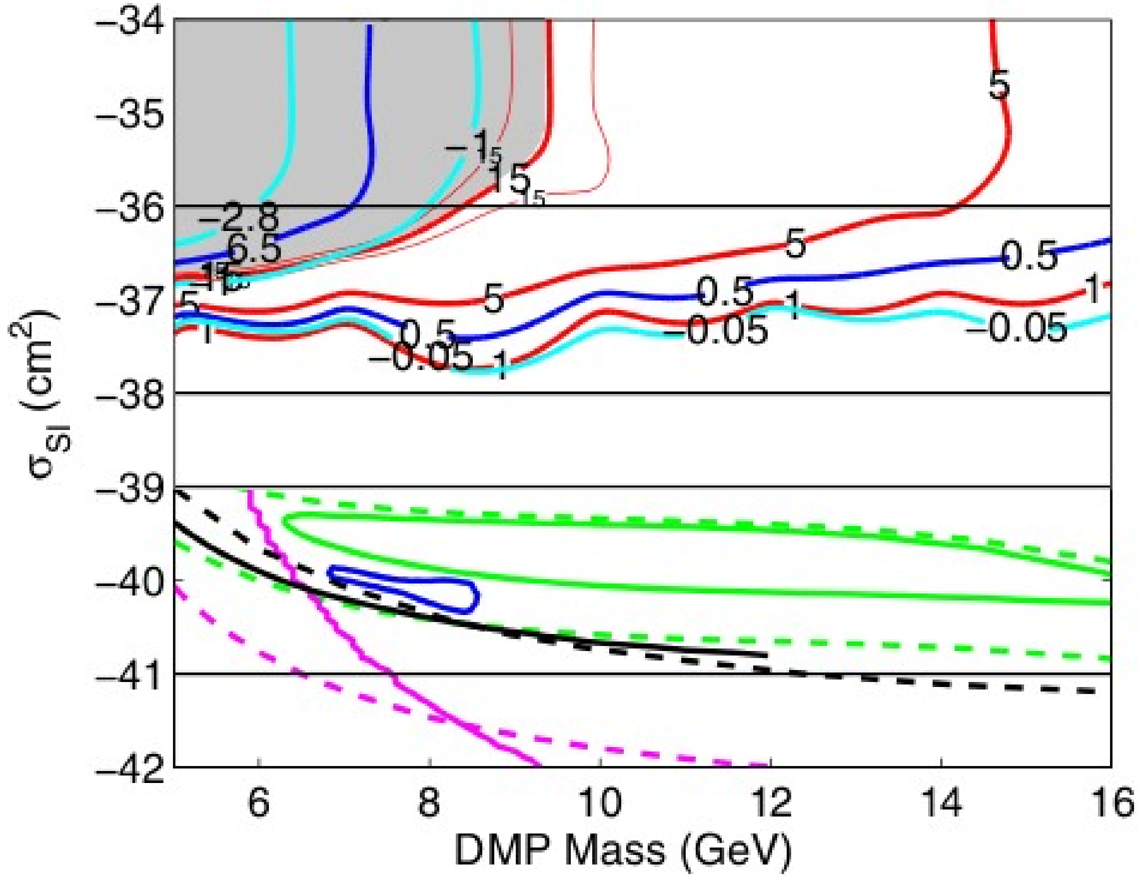
Comparison with direct detection

Significant improvements of the bounds from DD during last years



Spin Independent couplings

For Spin-independent couplings direct detection experiments do better because Sun is mainly made of hydrogen and SI interactions are coherently enhanced for heavy nuclei: $\sigma \sim A^2$

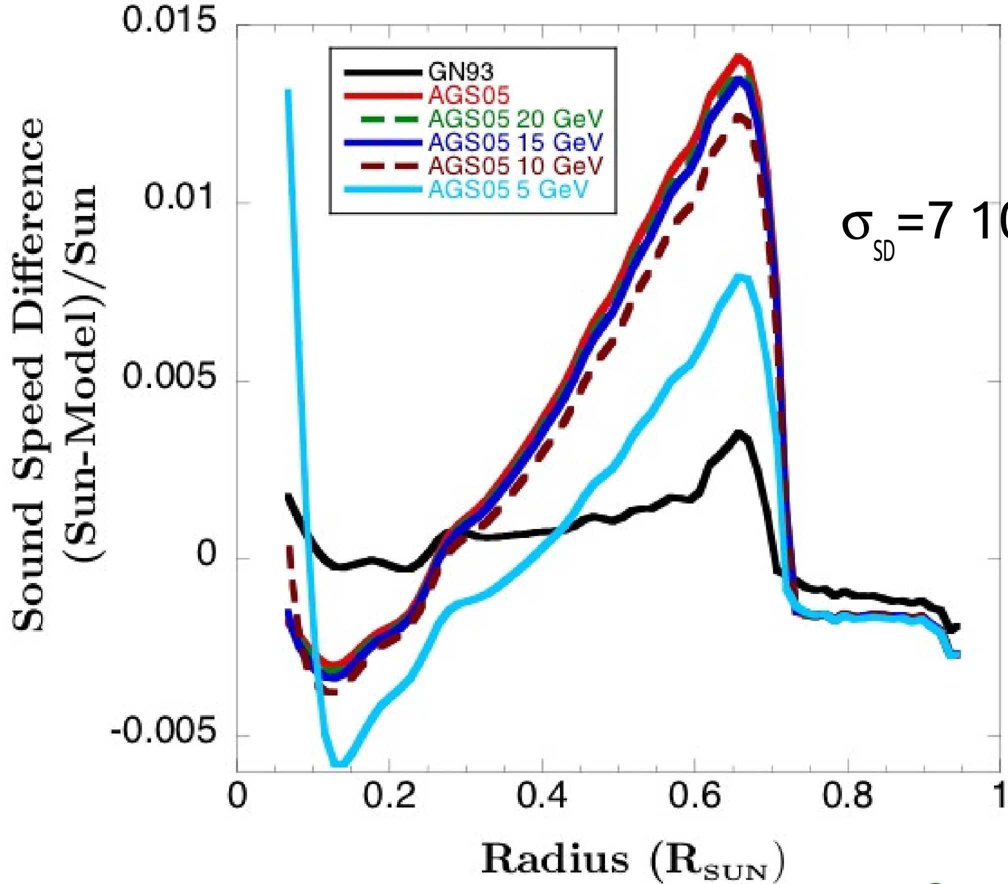


Lopes et al. 2012

Helioseismology

Sound speed profile can also constrain DM

However bounds are less strong than those from neutrinos



σ_{SD}=7 10^{-35} cm^2

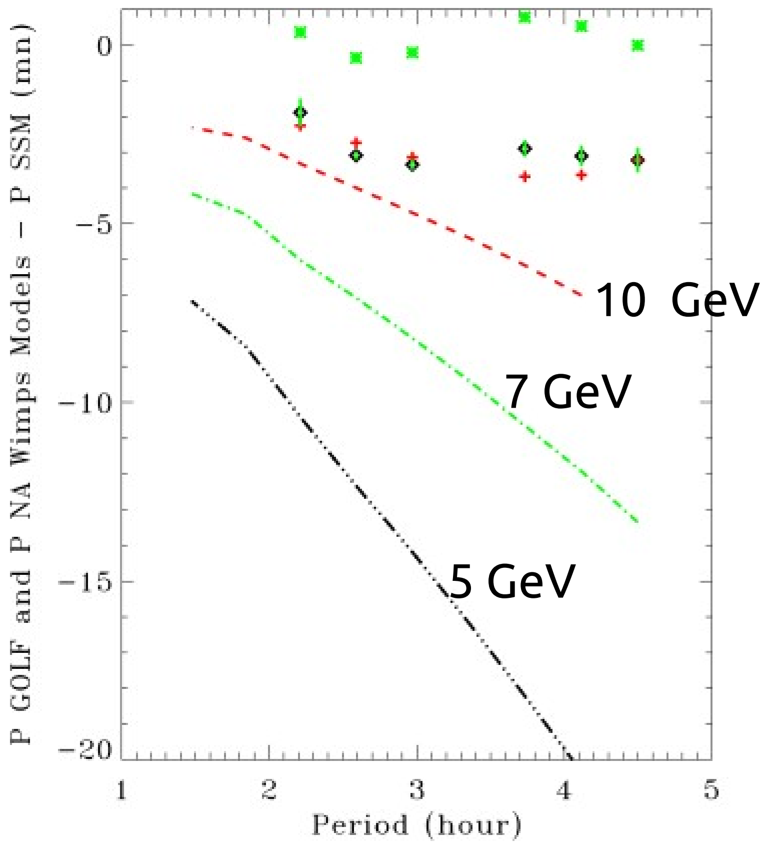
Cumberbatch et al. 2010

Solar gravity modes

See talk by Turck-Chieze

Gravity modes are promising

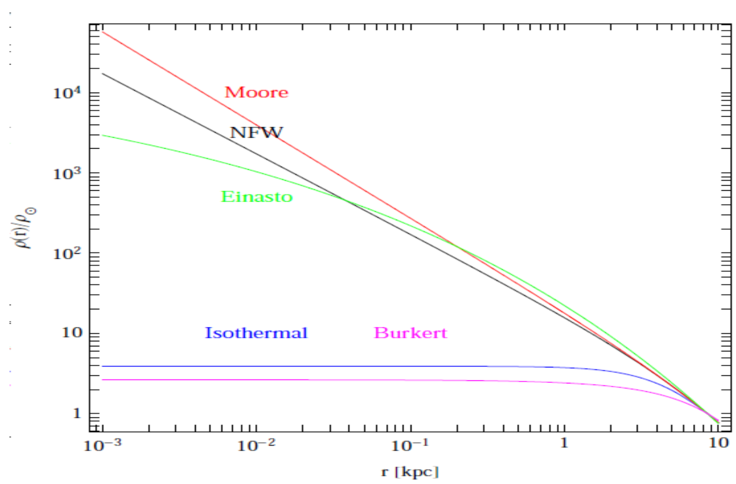
σ_{SD}=5 10^{-36} cm^2



Turck-Chieze et al. 2012

Stars in high DM density environments

At the center of the halos DM density should be larger than the local value

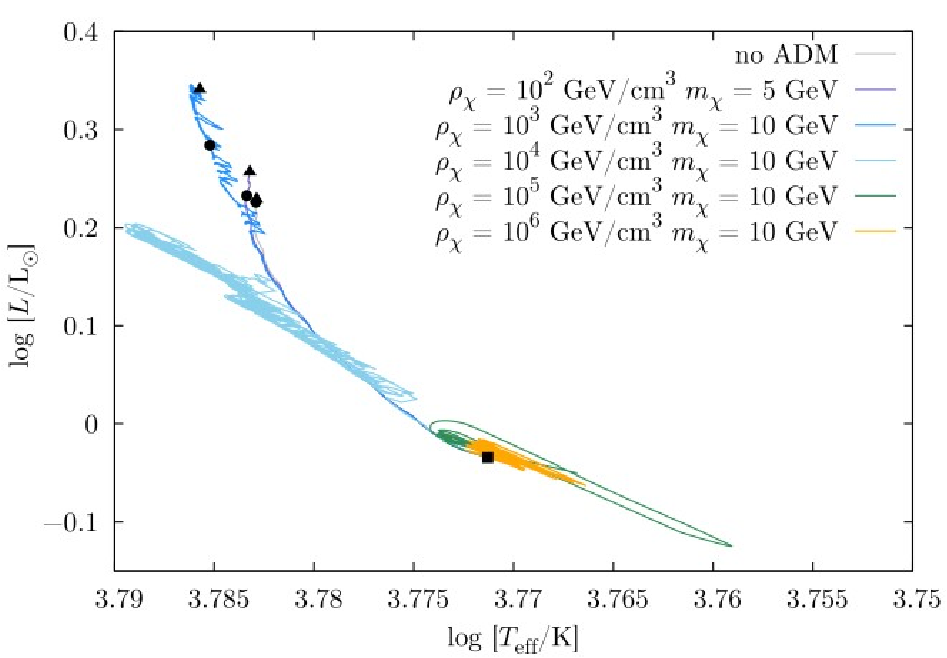


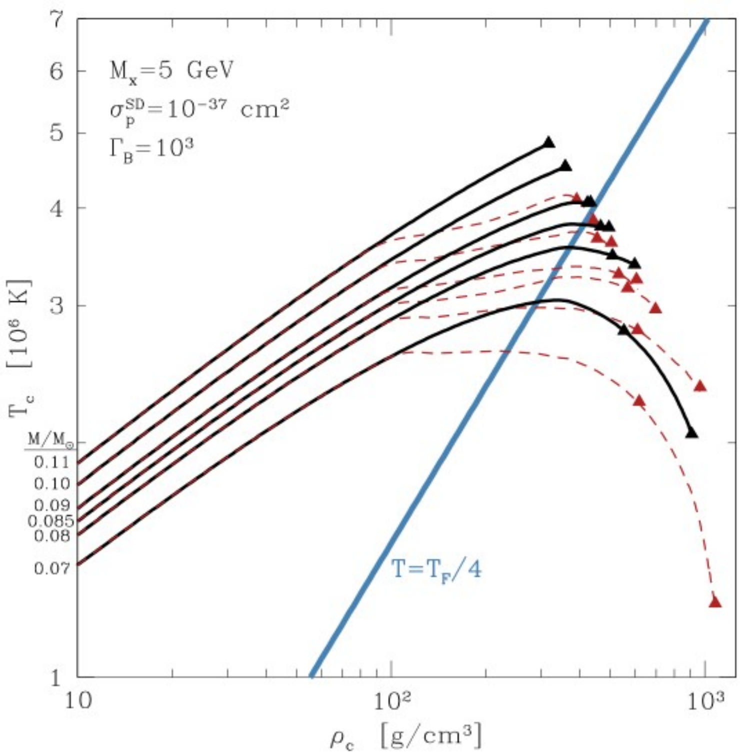
DM Capture on stars can be much dramatic than those occurring in the Sun

Stars in high DM density environments

Stars are cooler and dimmer

Effects: deviations on HR diagram & increase of the minimum mass for Main Sequence H-burning.





Iocco, MT, Meynet, Leclerq 2012

Zentner, Hearing 2012

Conclusions

DM in the SUN

- Annihilating DM:

  no effects on the structure of the Sun.

  Look for HE neutrinos from DM annihilations.

- Feebly (or non) annihilating DM:

  Solar neutrinos and helioseismology data constrain light DM candidates

  Direct detection bounds are generally stronger

EXOTIC STARS

Possibly anomalous evolution of stars

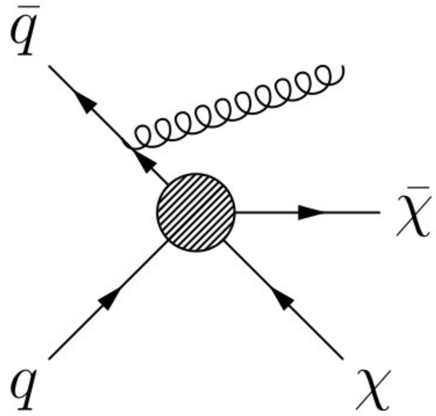
Collider bounds

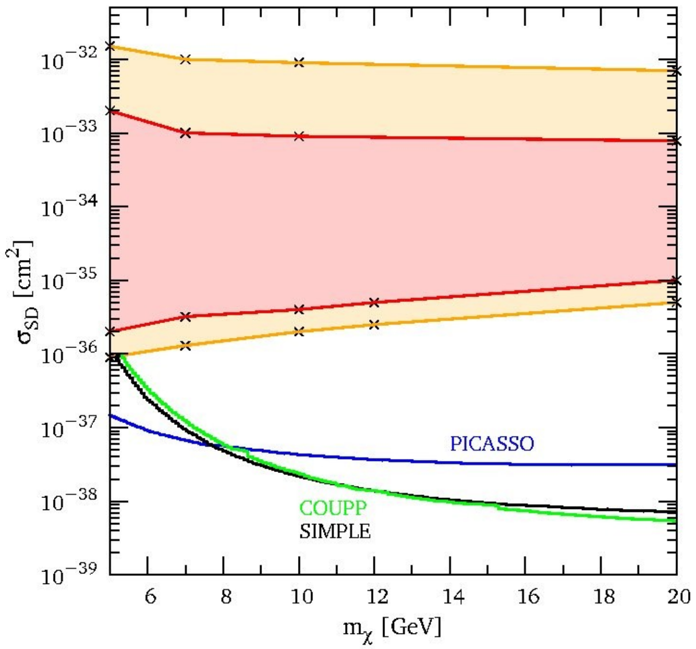
Effective DM-quarks coupling can be probed at collider

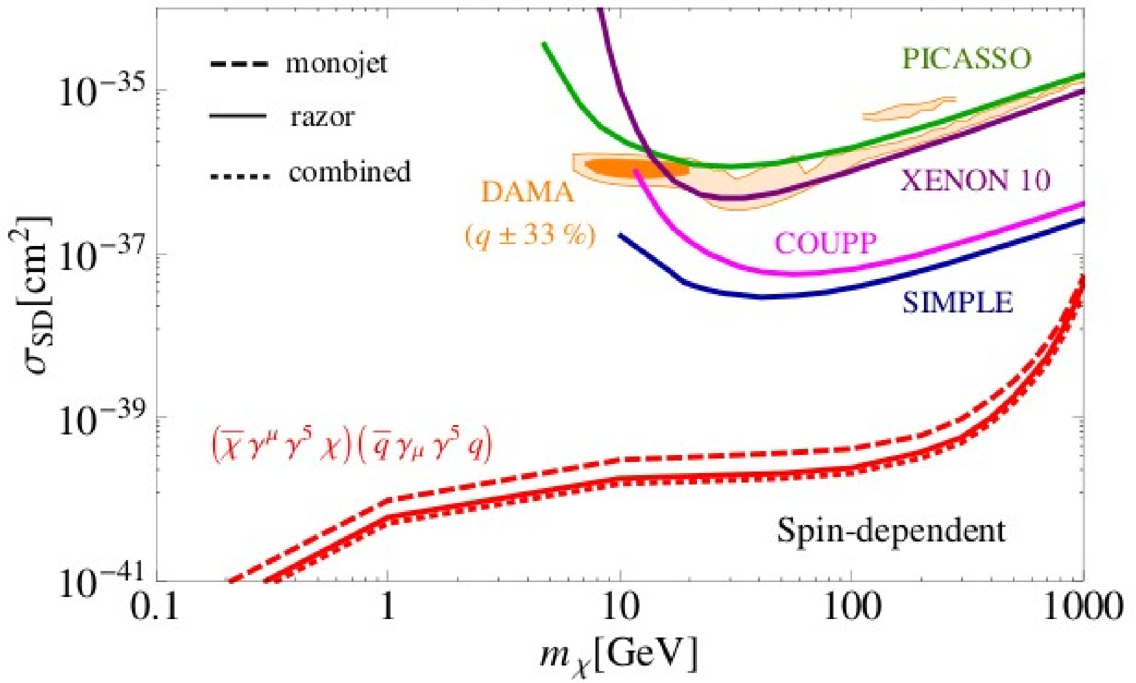
Searches: Mono-jet (photon, Z)

One can use Effective Field Theory with contact interactions

to parametrize the process





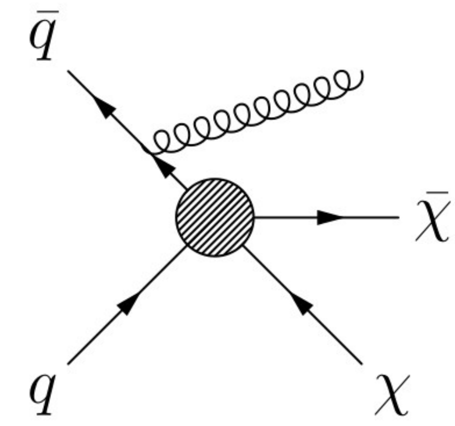


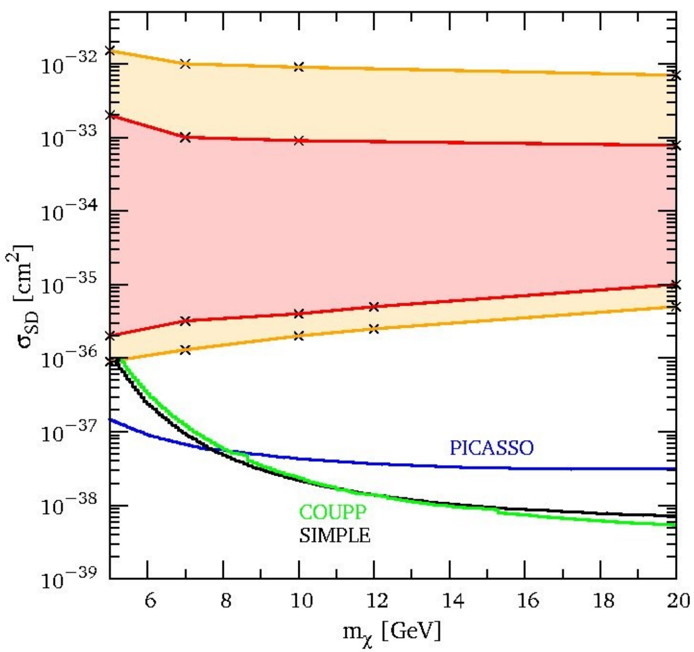
Fox et al. 2012

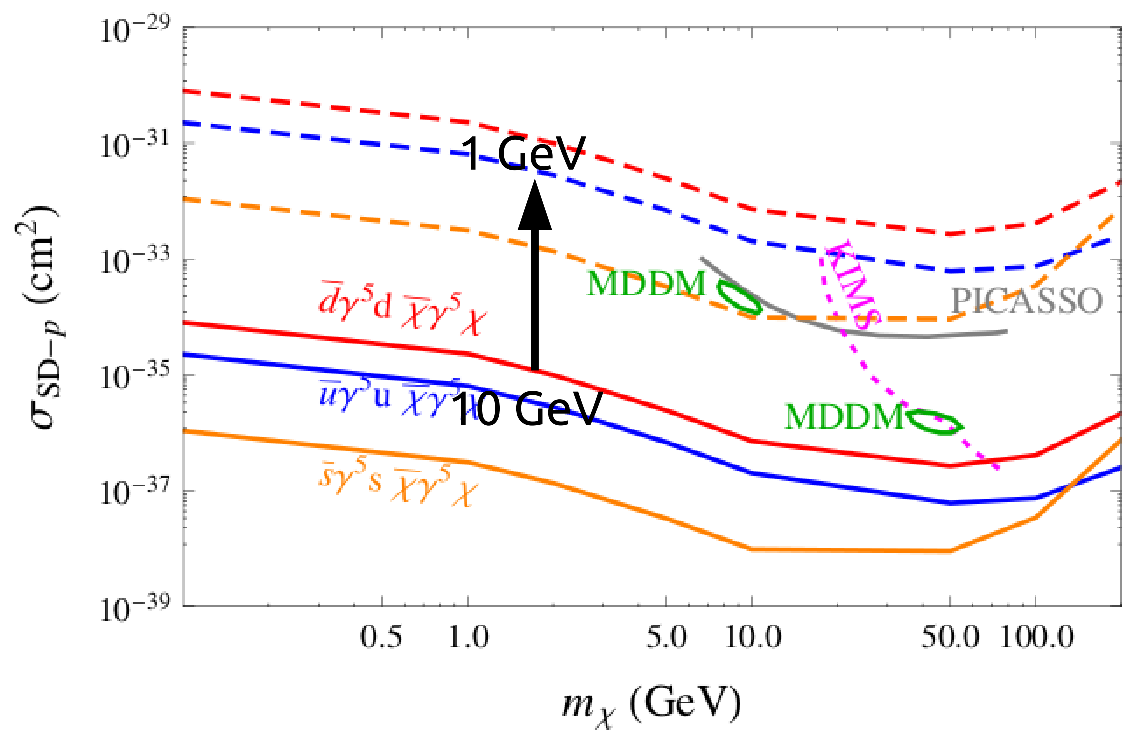
Comparison with colliders

Mono-jets bounds are very strong for light DM

However EFT is not longer a good description for light mediators and bounds can be too stringent







Bai et al. 2010