DOUBLE DISK DARK MATTER

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OUTLINE

- Motivation and Basic Idea
- Constraints on Double-Disk and the Allowed Parameter Space
- Direct Detection and Solar Capture
- Conclusions and Outlook

WHAT DO WE KNOW ABOUT THE DARK MATTER?

$$\Omega_{DM} h^2 = 0.12$$

- DM is mostly collisionless. Self-interactions are (weakly) constrained
- The DM is most likely cold
- Most of the matter in the Milky Way, as well as in other Galaxies is dark, distributed in elliptical halos

Most of the constraints on the DM are derived assuming that the DM is single component.
Can we have interesting signatures from a subdominant dissipative component of the DM?

SIGNALS OF DISSIPATIVE DARK MATTER

Expect that a dissipative DM component has a different spatial and velocity distribution than the dominant DM component

What can be affected?

- **Direct detection (velocity distributions change)**
- **Stellar capture**
- **Indirect detection (different density profiles)**
- **Trajectories of stars**

Even a subdominant DM component can lead to unusual effects

DARK GALACTIC DISK

What is the mechanism of a Galactic disk formation?

Vogelsberger, Torrey, Sijacki, Keres, Springel, Hernquist; 2011

The baryonic matter collapses into a disk as it cools down. No Supernova or other stellar feedback is needed for disk formation.

Needed for disk formation in the dark sector:

- Cooling mechanism
- $t_{cooling} << t_{Universe}$ Even if $t_{cooling} \simeq t_{Universe}$ we can get interesting effects

COOLING DYNAMICS IN A VIRIAL CLUSTER

- Compton scattering. Cooling down of electrons when they scatter on cold CMB photons. Usually it is completely subdominant to other processes if $z < 10$. Not clear if Galaxies can form so early. This can change in the dark sector

- Bremsstrahlung radiation. Electrons scatter on protons in hot plasma. In the baryonic sector this is usually a dominant cooling mechanism for cooling all the way down to the temperatures ~ (0.1 ... 0.01) B.

- Collisional cooling due to “molecular processes”, for example $H + e^- \rightarrow H^- + \gamma$. These processes can cool dow some regions all te way down to O(100 K) and allow star formation. We will assume, that there are no such processes in the dark sector.

COOLING IN THE DARK

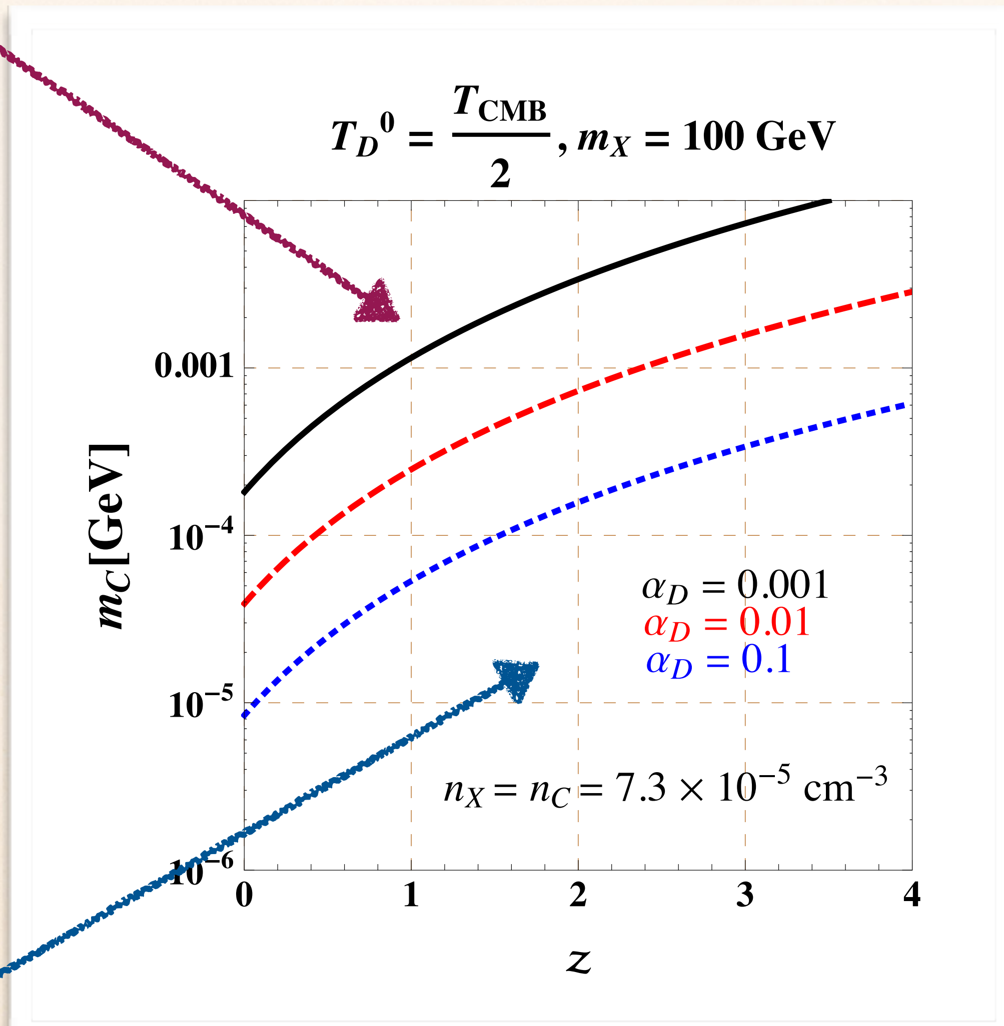
- Need a long range force in the hidden sector: neither Compton nor Bremsstrahlung are possible without this force. Assume $U(1)_D$ which leads to dissipative dynamics.

- Need a light DM component to allow a cooling which is fast enough, $t_{Brem} \propto m^{3/2}$, $t_{Comp} \propto m^3$. This is an electron-like DM component (C).

- In order to allow Bremsstrahlung we need also a proton-like heavy component (X).

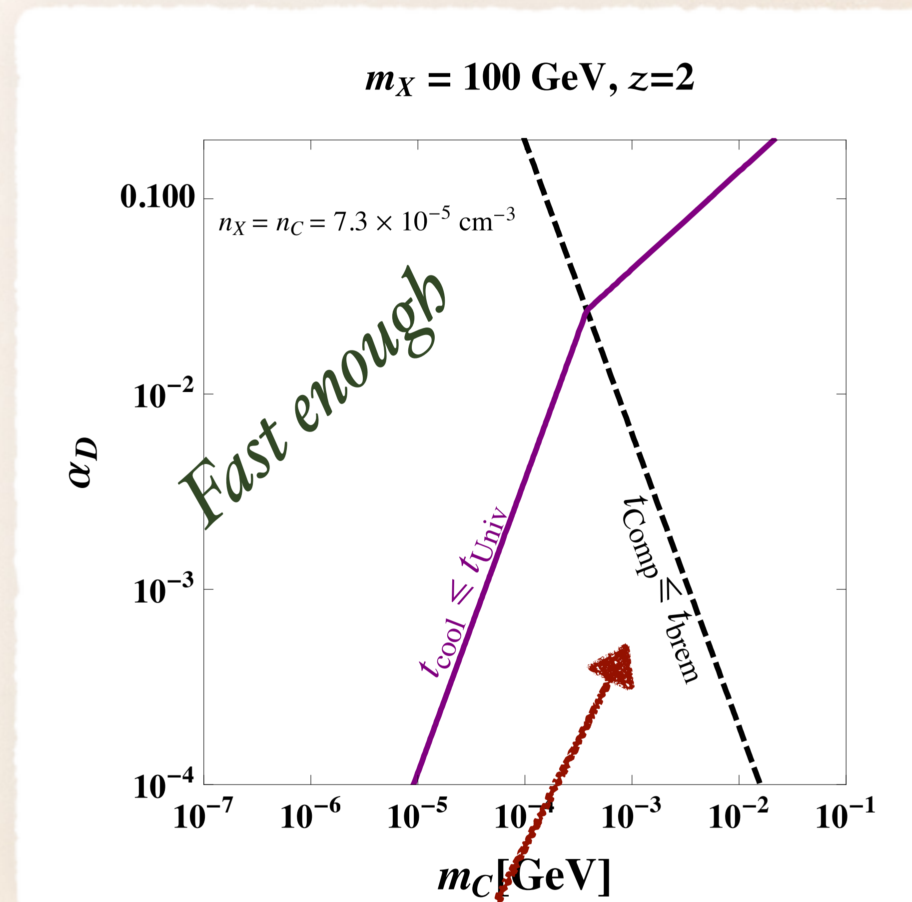
HOW DOES DDDM COOL DOWN?

Bremsstrahlung-dominated



Compton-dominated

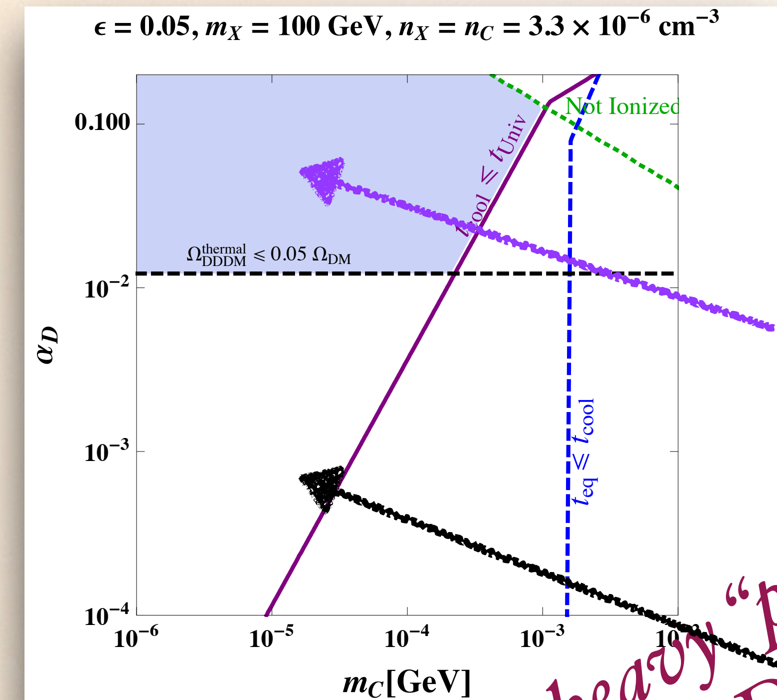
Does it cool down fast enough?

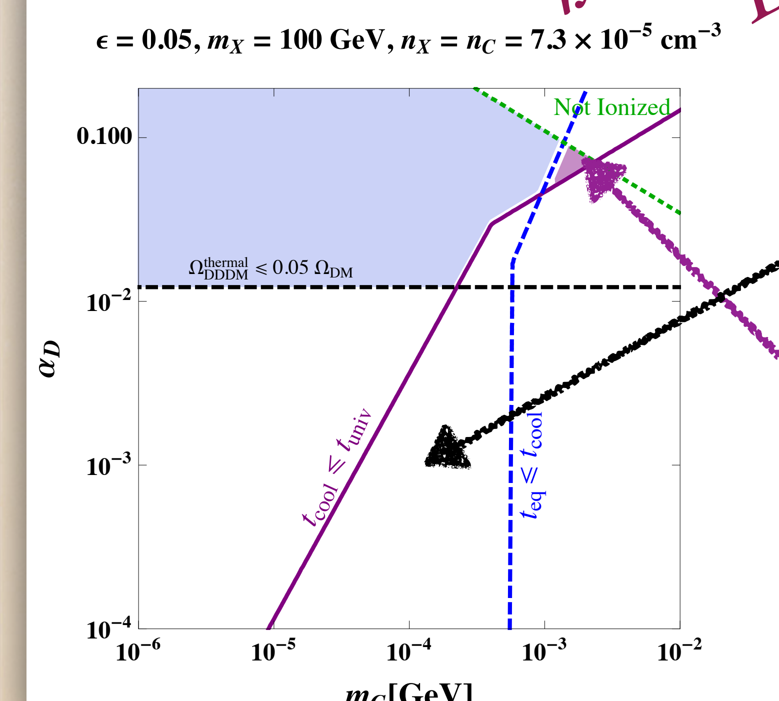


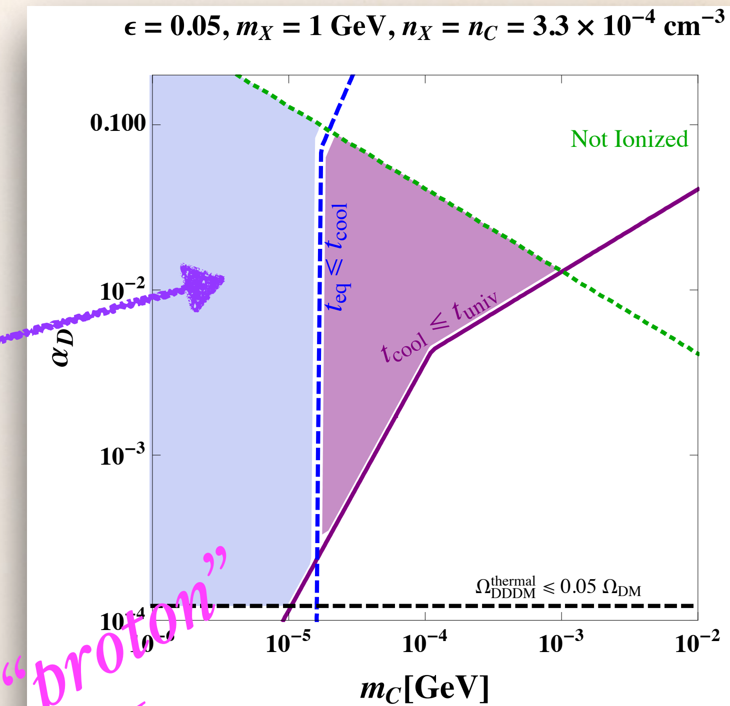
Cooling is too slow

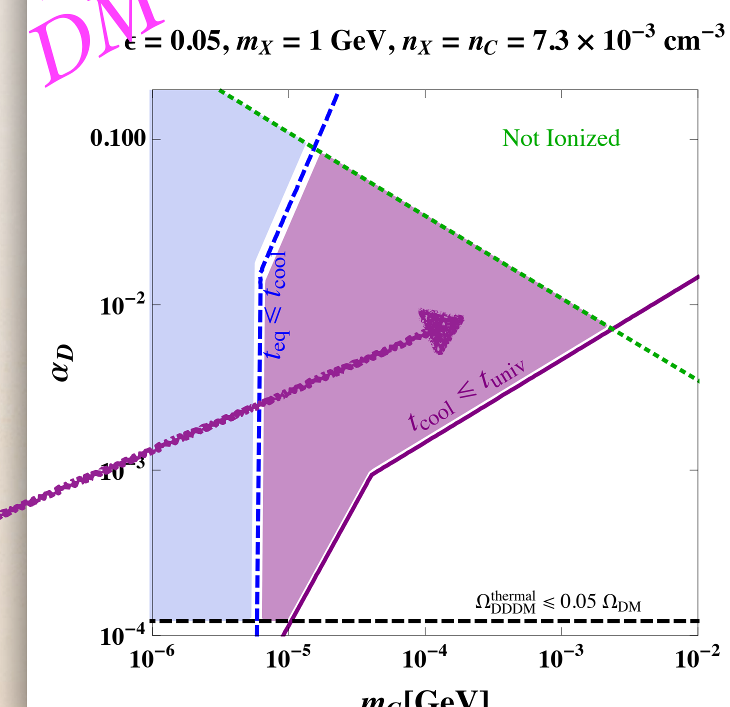
EFFICIENCY OF DARK COOLING

$$z = 2, \quad T_D = T_{CMB}/2$$









cools down non-adiabatically

heavy "proton" DM

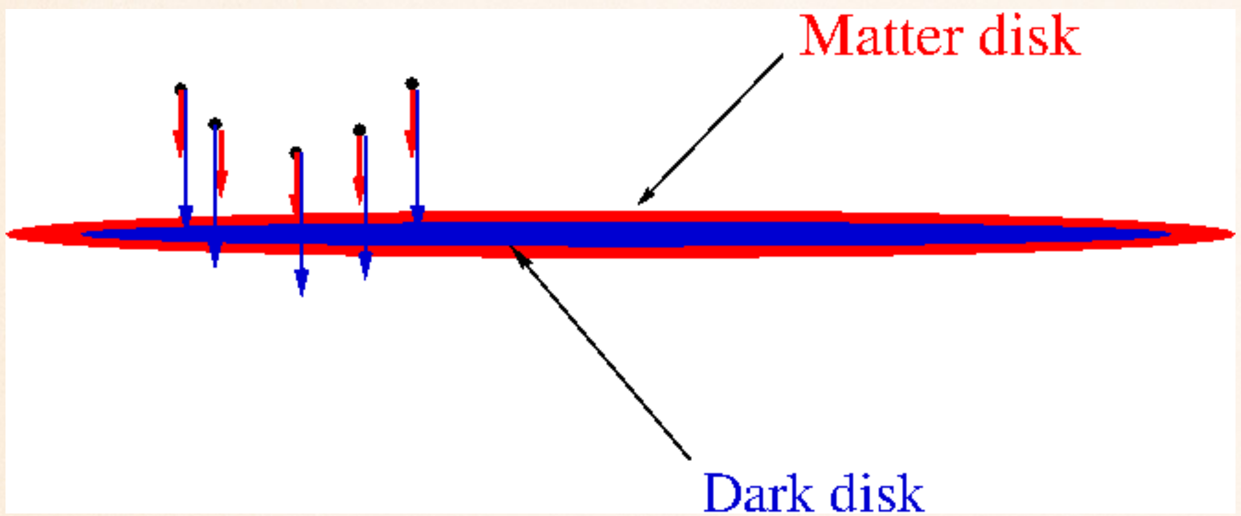
light "proton" DM

the symmetric component is thermally overproduced

cools down adiabatically

FRACTION OF DDDM IN THE MILKY WAY

Oort limits



$$\int_{-z_0}^{z_0} \rho(z)dz \propto \frac{\partial_z \Phi}{G_N}$$

We used in our estimates

$$\Sigma_{vis,\,1.1} = 35\ldots58\ \frac{\mathrm{M}_\odot}{\mathrm{pc}^2}, \quad \Sigma_{tot,\,1.1} = 71 \pm 6\ \frac{\mathrm{M}_\odot}{\mathrm{pc}^2}$$

Our constraints: inside the Milky Way $\quad \frac{\Omega_{DDDM}}{\Omega_{DM}} \lesssim 0.05\%$

Later developments — Bovi & Rix (2013) claim that the error bars on the visible matter can be significantly shrunk and constrain this ratio to be ≲ 2.5%

CONSTRAINTS ON SELF INTERACTIONS

Bullet Cluster Constraints

The results are usually phrased as constraints on self-interactions cross sections. If we phrase them as constraints on the fraction of self-interacting DM, we get ≲ 30% can be self-interacting

Bounds from the Shapes of the Galactic Halos

Peter, Rocha, Ballock, Kaplinghat; 2012

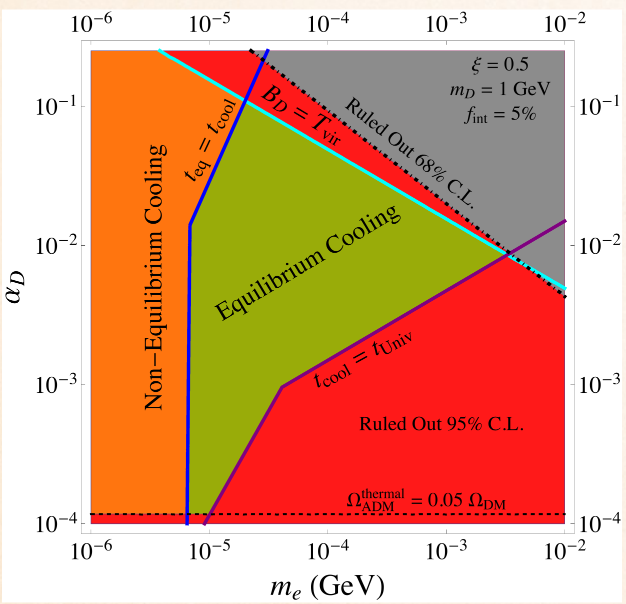
Basic idea: self-interacting DM forms for spherical haloes $\frac{\sigma}{m} \lesssim 0.2\,\frac{\text{barm}}{\text{GeV}}$

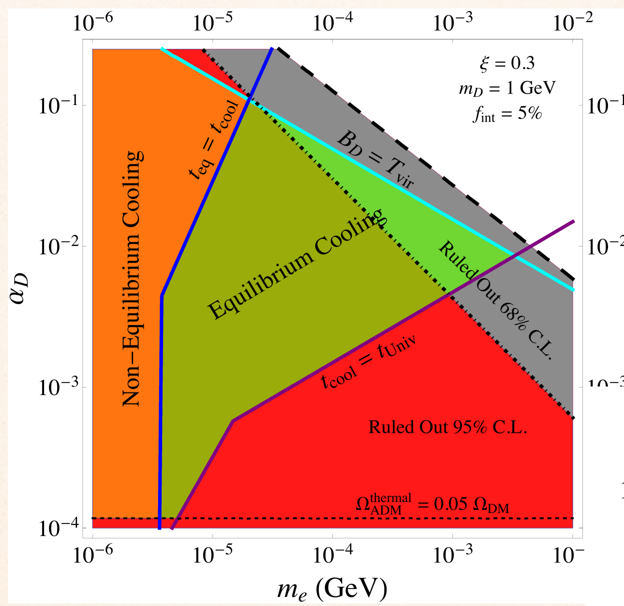
Hard to interpret in terms of multi-component DM, but 15% of SIDM is probably safe.

COSMOLOGICAL CONSTRAINTS ON DDDM

Cyr-Racine, de Putter, Raccanelli, Sigurdson; 2013

In the early Universe the DDDM is coupled to the dark radiation, leading (similar to BAO) to dark acoustic oscillations with a characteristic frequency. This should leave imprints on the CMB and the large scale structure.



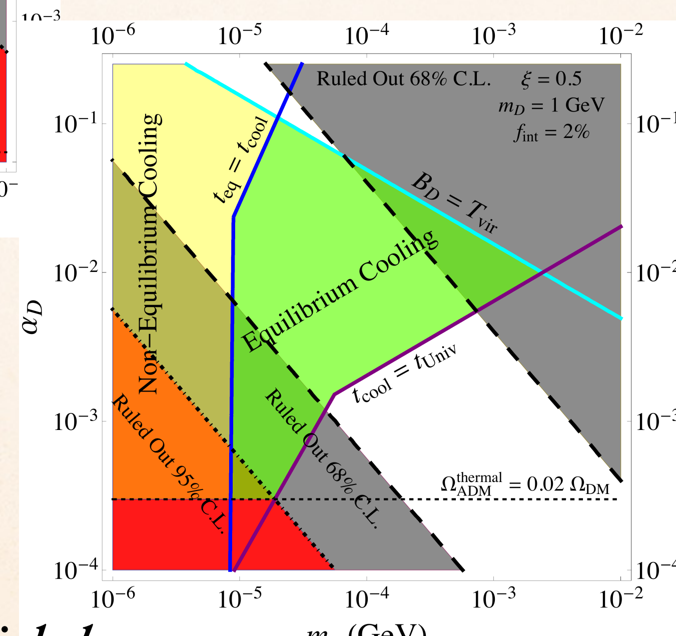


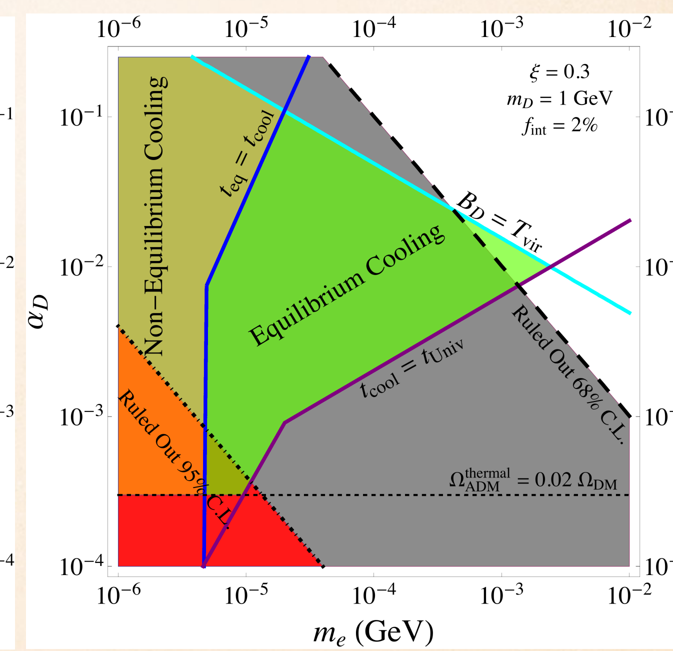
almost no parameter space left for

$$\Omega_{DDDM} = 0.05\,\Omega_{DM}$$

More reasonable values:

$$\Omega_{DDDM} = 0.025\,\Omega_{DM}$$





Planck+WMAP+BAO+High-l

OVERVIEW OF THERMAL HISTORY OF DDDM

- A-priori we know nothing about the interactions of the hidden sector with the baryons. We assume that they interact at the weak scale, but this is not promised. Slightly below the EW scale the dark sector decouples from the visible sector.

- Below that scale the heavy component X freezes out.

- Below the freeze-out scale the recombination process between heavy particles start. This should not wash out the heavy symmetric component

- Below the mass of the light component C dark recombination process starts (X recombines with C). We should have enough light DM particles at this point.

CONSTRAINTS ON KINETIC MIXING

The dominant constraint on the kinetic mixing comes from a possibility that after the decoupling between the sectors, the light DM C might re-equilibrate with the SM photons. The rate for CC⇔ɣɣ ~ T, while the Hubble rate ~ T^2. This might have an impact on BBN. To avoid this we need the kinetic mixing ≲ 10^{-9}

When does this happen?

- If the dark EM and the hypercharge are embedded into one non-Abelian group
- No particles, which are charged simultaneously under the hypercharge and the dark EM, while all other interactions are due to Yukawa-type couplings
- There are states, which are charged under both U(1), but they satisfy anomaly like conditions $\mathrm{Tr}\left(Q_Y^m Q_D^n\right) = 0$

DDDM DIRECT DETECTION DIFFERS FROM CDM

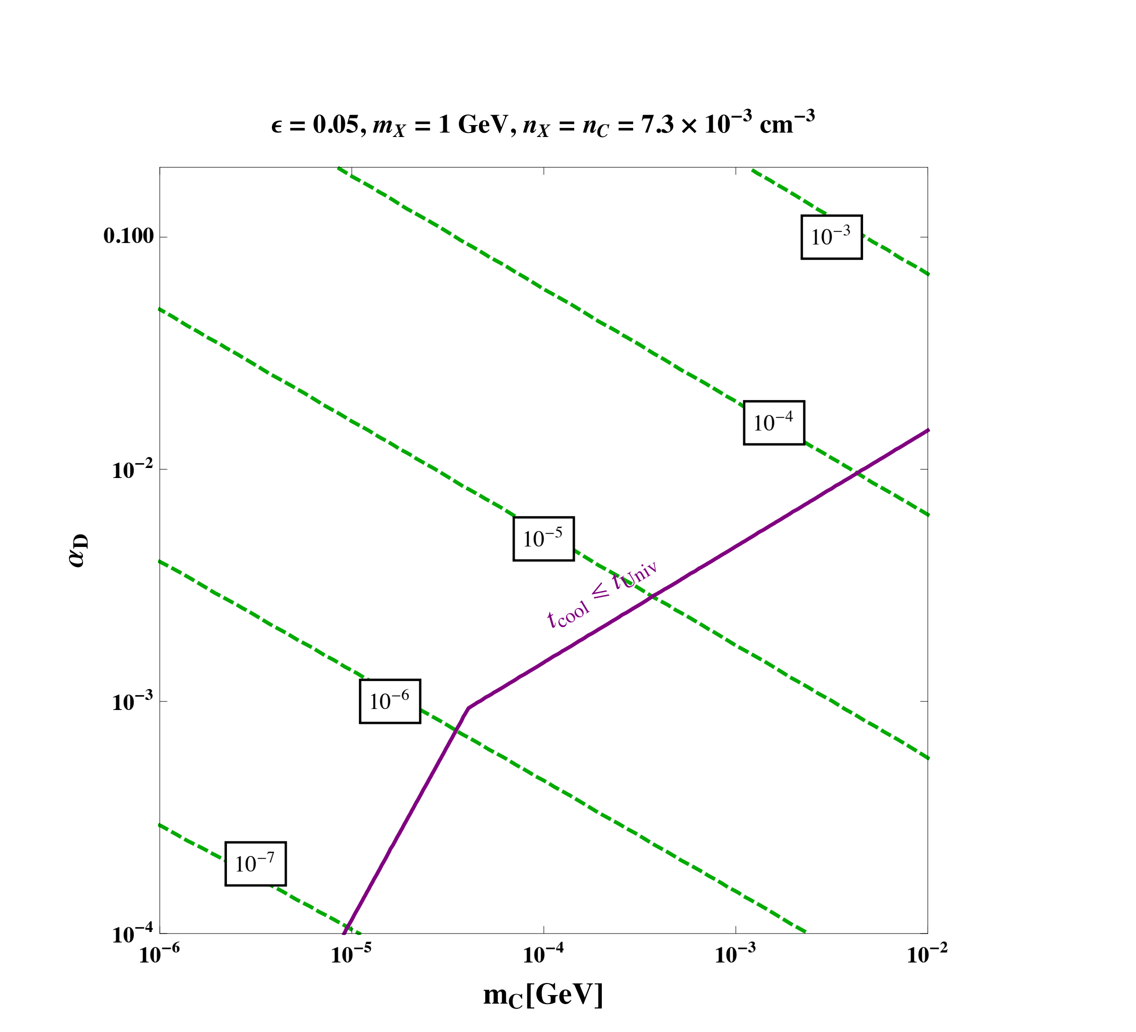
The recoil energy in direct detection experiment varies from zero to maximal recoil energy

$$E_{max}^{recoil} = \frac{2\mu^2}{m_N} v_X^2$$

Dissipative DM tends to have smaller velocities than CDM ➪ expect smaller recoil energy than the CDM and weaker bounds than the bounds on the CDM.

RELEVANT VELOCITIES

Naively we can get velocities as small as 10^{-7}



For CDM we usually have

$$\bar{v} \approx |\vec{v}_{rel}| \approx 10^{-3}$$

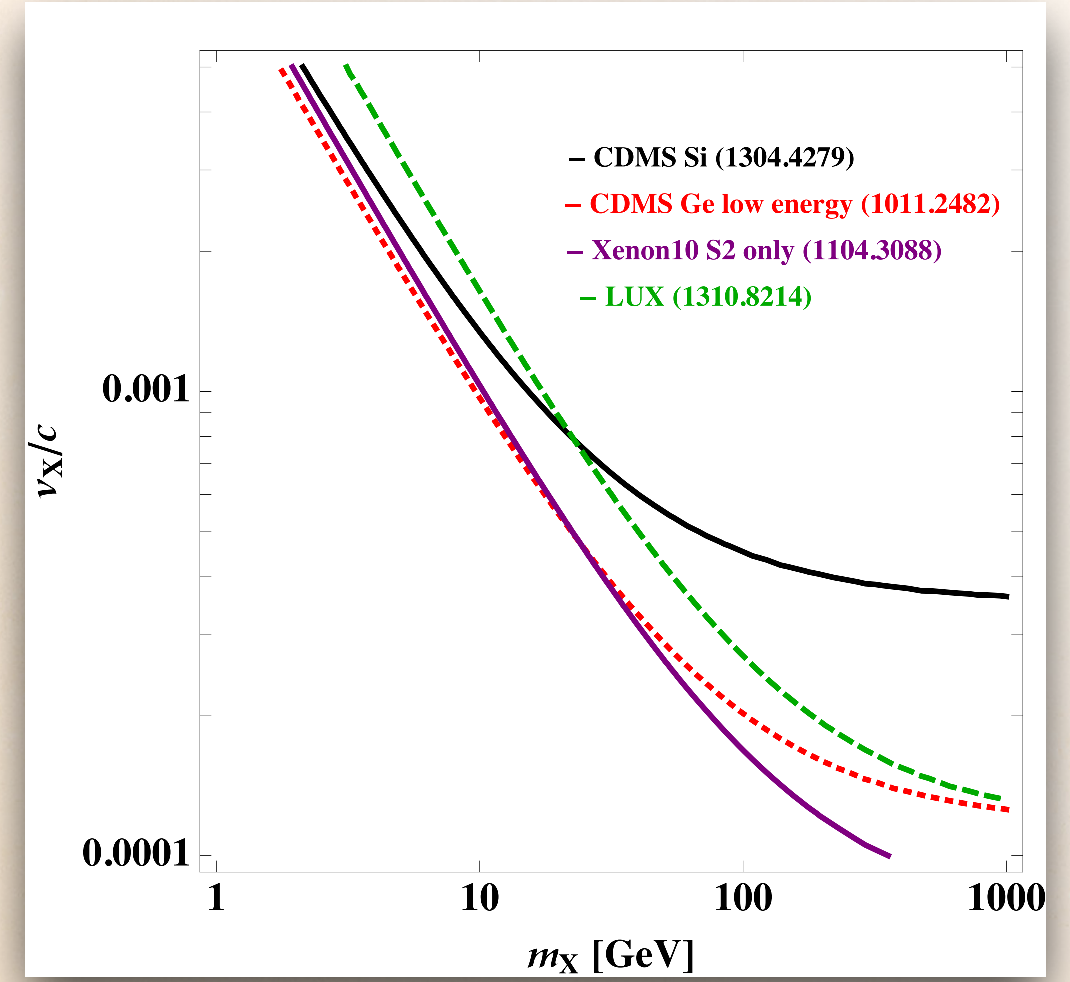
If dissipative DM has enough time to collapse to a disk. The dark disk co-rotates with the baryonic disk around the Galactic Center.

$$\bar{v} \sim |v_{\rm rel}^{\oplus}| \lesssim 10^{-4}c$$

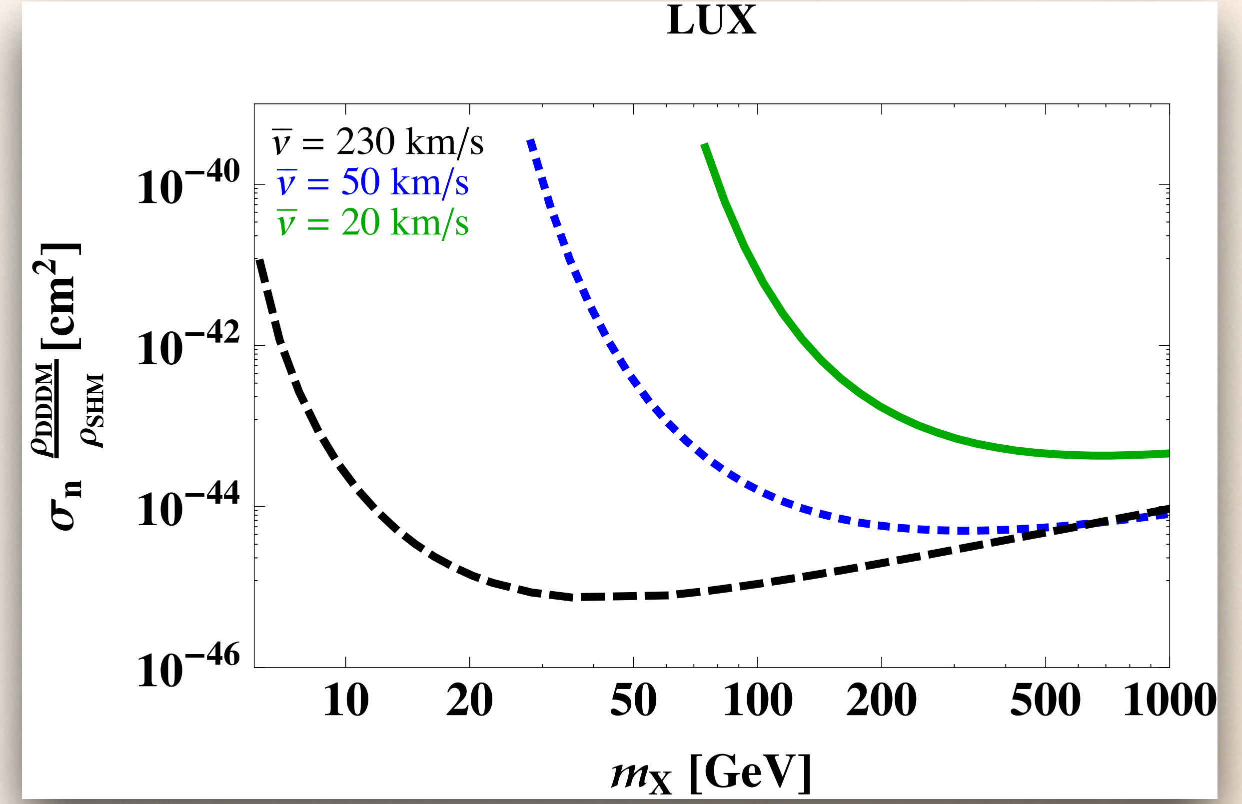
This is the smallest velocity that we consider

DISSIPATIVE DM AND DIRECT DETECTION

Sensitivity of various direct detection experiments to the DM velocities



Recast of LUX results:



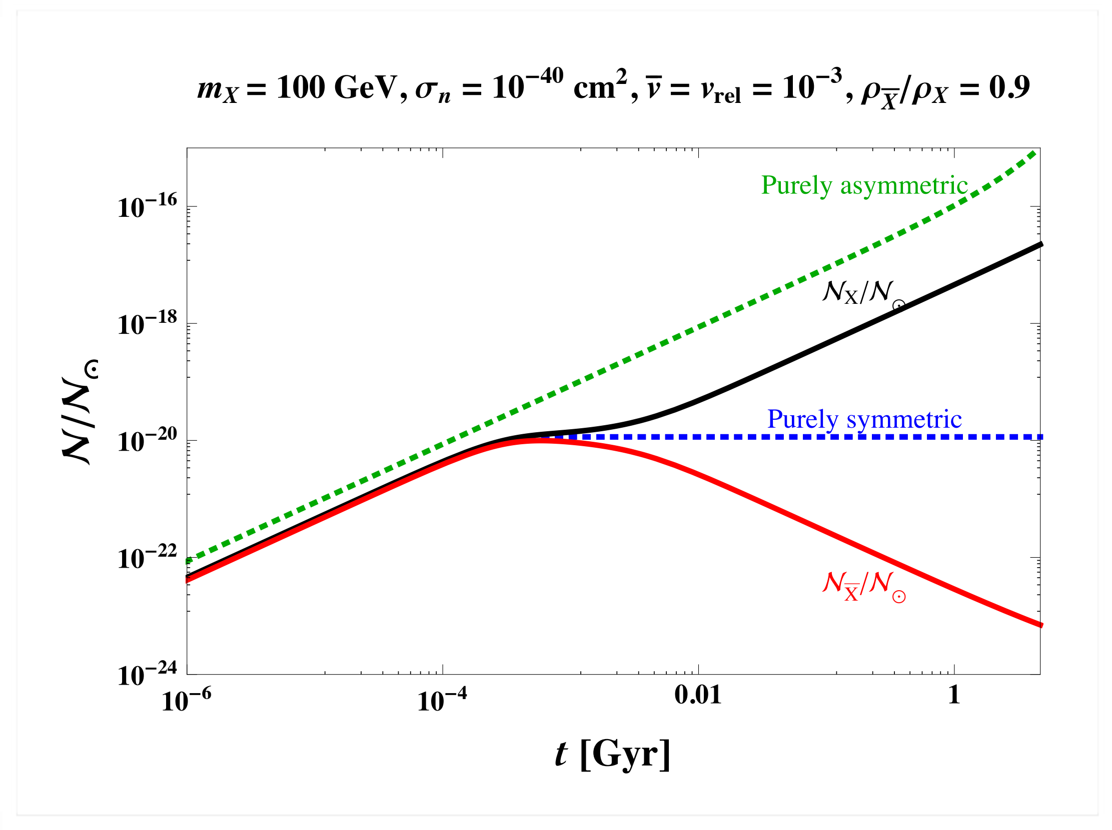
As expected the bounds on dissipative DM is weaker than on CDM

THE FIRST LOOK ON SOLAR CAPTURE

- The mean velocity is different from the CDM
- The DM is self-interacting, the self-capture is important
- The DM is partially asymmetric. The light component (C) must be asymmetric. The heavy component has both symmetric and asymmetric components
- Both free heavy particles and dark atoms can be captured
- In the dissipative regime the binding energy of the dark atoms is smaller than the solar temperature.

ASYMMETRIES AND SELF-INTERACTIONS

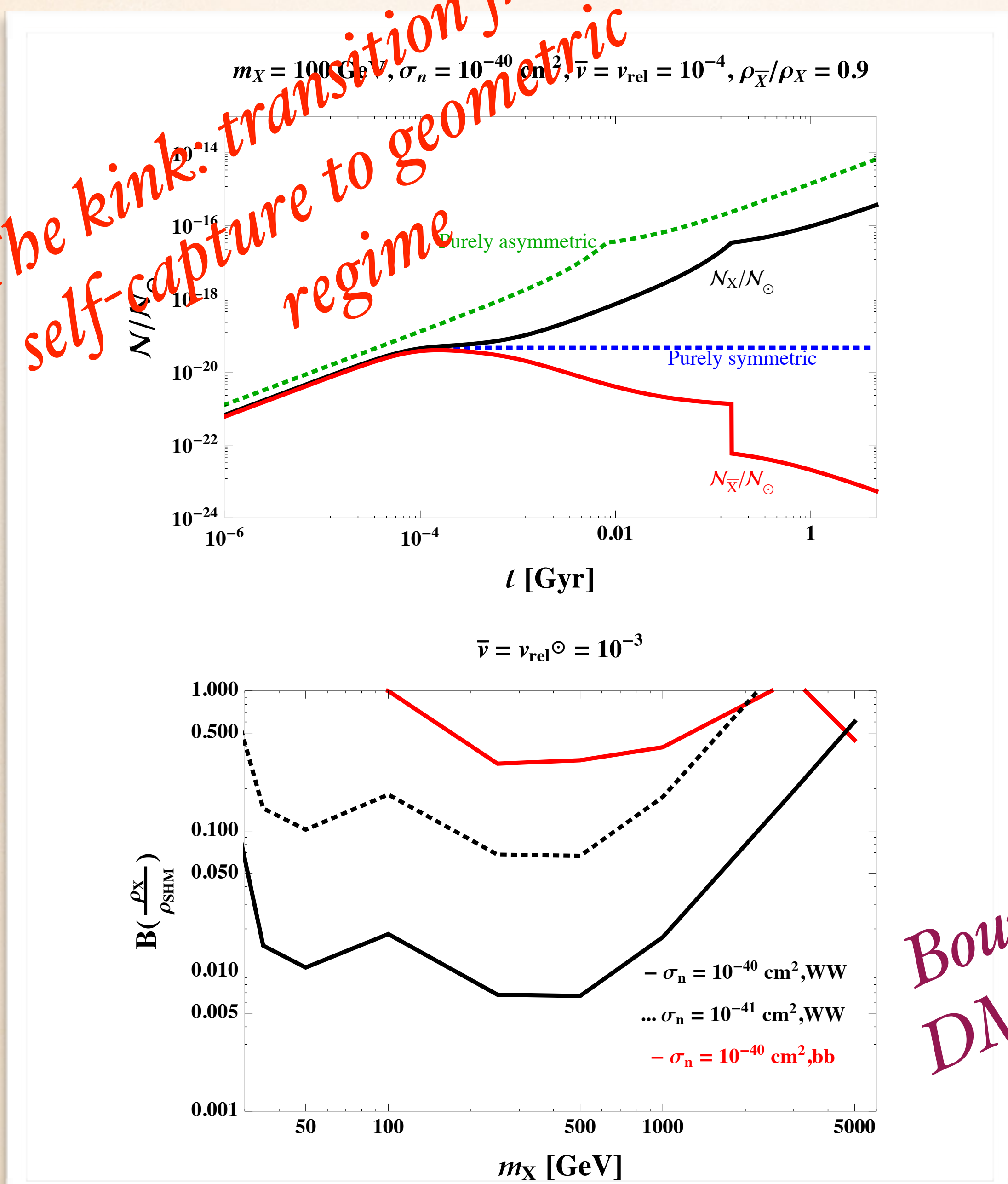
If the DM is purely asymmetric, it is linearly accumulated in the star. Purely symmetric asymptotes to a constant value. In partially asymmetric case the equilibrium is never reached.



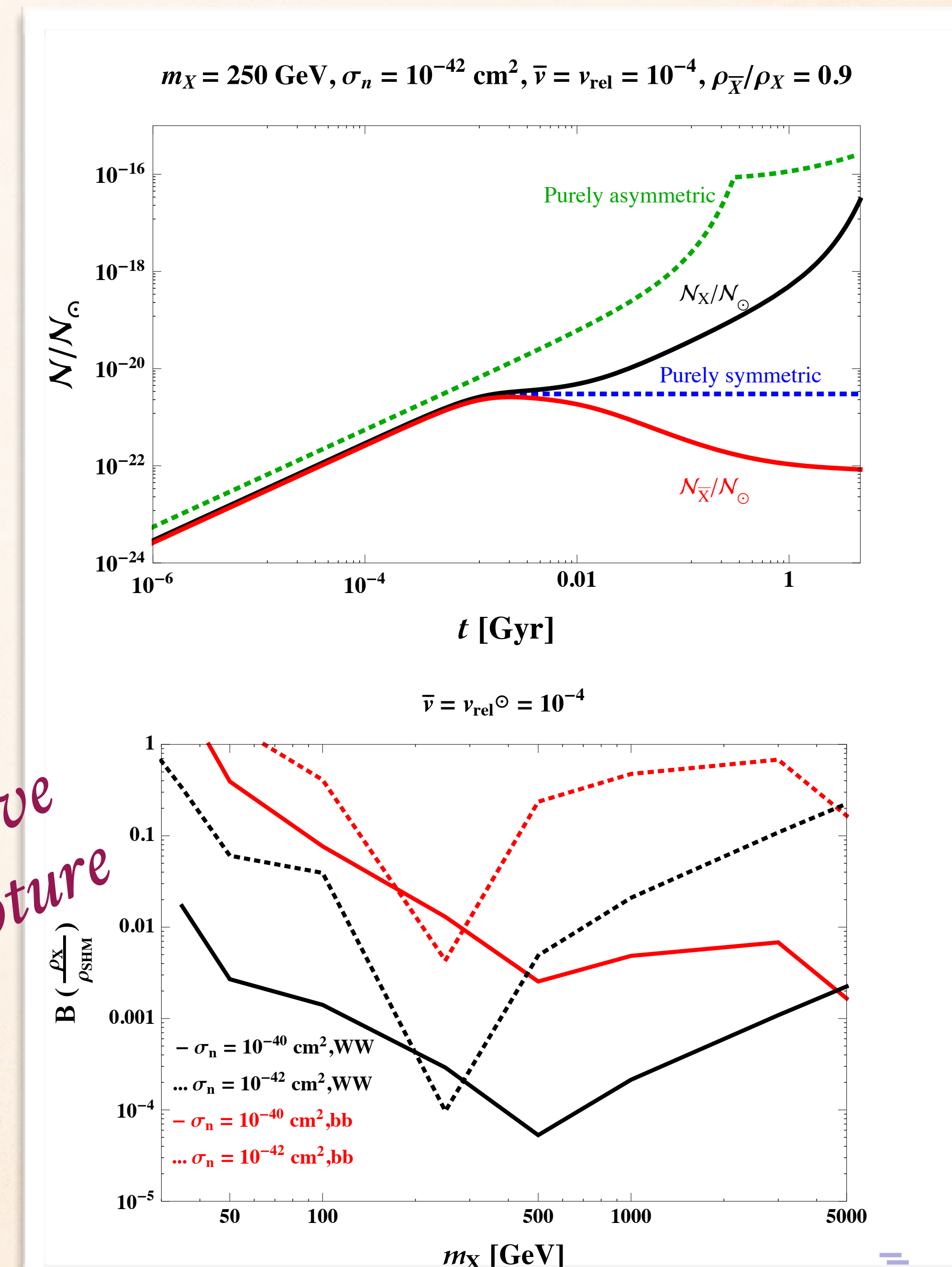
- The capture in the young stars is mostly the nuclear capture
- When the amount of the captured DM gets to some critical value, the exponential growth due to self capture is triggered
- The exponential growth is brief, the effective cross section is saturated
- The capture further proceeds similar to the nuclear capture, but with a different saturated cross-section.

SOLAR CAPTURE: RESULTS

The kink: transition from self-capture to geometric regime



Bounds on dissipative DM from solar capture



CONCLUSIONS AND OUTLOOK

- Partially dissipative DM is viable possible which can potentially lead to rich dynamics and interesting phenomenology

- Would be interesting to analyze DDDM with explicit simulations and further constrain it (or maybe find some hints for its existence)

- The direct bounds on the interactions of partially dissipative DM are relaxed compared to the bounds on CDM

- We get interesting bounds from the solar capture; the self-capture effects are important