Looking for Dissipative Dark Matter

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work in progress

Rutgers
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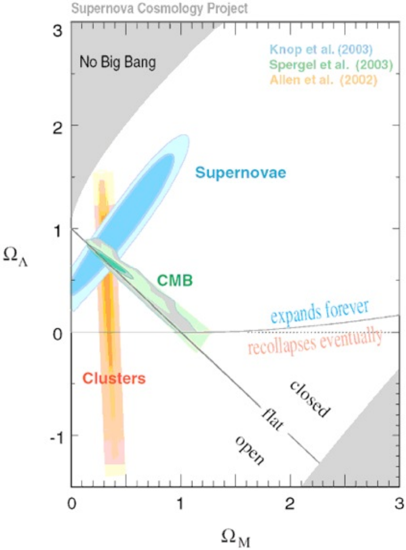
Dark Matter



- Ample gravitational evidence, both direct and indirect, that dark matter comprises a large fraction of the universe.

Particle properties of dark matter

- Thermal WIMPS:
  - connection to EW scale well-motivated
  - (relatively) few unknown parameters
  - largely inform ongoing and exciting DM experimental programs
- Nontrivial dark sectors
  - may address other outstanding problems in the SM (e.g. baryogenesis)
  - may address puzzles in cosmological structure formation?
  - can yield qualitatively distinct signals

Dark matter with long-range interactions

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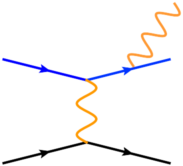
  - ...largely obviated if only $\lesssim$ 10% of DM has appreciable self-interactions
- Nontrivial particle constraints (kinetic mixing, ...)
- Nonetheless, dark sectors with e.g. unbroken $U(1)_D$ still consistent with all astrophysical data

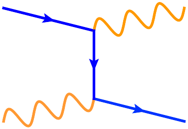
(Ackerman, Buckley, Carroll, Kamionkowski; Cyr-Racine, Sigurdson; ...)

Dissipative dark matter

- If DM has long range interactions, it may cool, losing energy via dark boson emission:



Brehmstrahlung



Compton

$$\tau_B \approx \frac{3}{16}\,\frac{n_X + n_C}{n_X n_C}\,\frac{m_C^{3/2} T_{vir}^{1/2}}{\alpha_D^3}$$

$$\tau_C \approx \frac{135}{64\pi^3}\,\frac{n_X + n_C}{n_C}\,\frac{m_C^3}{(T_D(1+z))^4 \alpha_D^2}$$

(Fan, Katz, Randall, Reese)

Dissipative dark matter

- Approximately, cooling via dark radiation continues until dark recombination, $T_D \lesssim B_{XC} = \frac{\alpha_D^2 m_C}{2}$
  - baryonic matter: further atomic and molecular heating/cooling. Neglect
- Then, velocity dispersion $\bar{v} = \sqrt{\frac{3T_D}{m_X}}$

$$\bar{v} = 10^{-4} c \frac{\alpha_D}{0.01} \sqrt{\frac{r}{0.1} \frac{m_C}{\text{MeV}} \frac{\text{GeV}}{m_X}}$$

(Fan, Katz, Randall, Reese)

Dissipative dark matter

- Efficient cooling requires a light particle C with abundance greater than thermal: asymmetric
- Assume endpoint of cooling is rotationally supported, as for baryonic matter
- Depending on spectrum and interaction strength, DM may be partially and/or non-adiabatically cooled

(Fan, Katz, Randall, Reese)

Dissipative dark matter: summary

Final picture:

- Subdominant partially ionized self-interacting dark sector consisting of
  - a light ($\lesssim$ MeV) particle C with an asymmetric relic abundance
  - a heavy ($\gtrsim 10\,\text{GeV}$) particle X and its anti-particle $\bar{X}$ with (in general) a symmetric as well as an asymmetric relic abundance
  - with equal and opposite charges under an unbroken $U(1)_D$
- Asymmetric X, C (partially) bound into dark atoms
- partially or wholly cooled with velocity dispersion $\bar{v}$ in the physically interesting range $10^3 - 10^4 c$

Observing dissipative dark matter

How can we detect the presence of a collapsed dark halo component?

- gravitational: thin, dense disks constrained by surface density studies (Weber, de Boer; Bovy, Rix)
  - constrains: $\frac{\Omega_{DDDM}}{\Omega_{DM}} \sim 0.05$.

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  - X interactions with nucleons: σ_N
  - $\mathcal{B} = \frac{\sigma(X\bar{X}\to SM)}{\sigma(X\bar{X}\to \text{anything})}$

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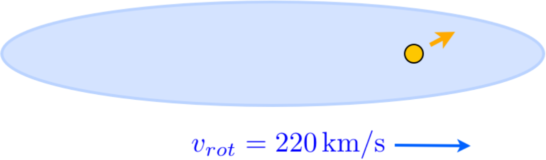
- See how direct and indirect detection can constrain DDM.

Some numbers

Typical galactic velocities:

$$\bar{v}_{SHM} = 505\,\mathrm{km/s}$$

$$v_{\odot} = (11, 12, 7)\,\mathrm{km/s}$$



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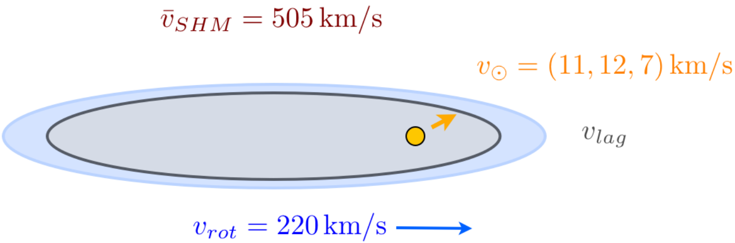

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v_{lag}

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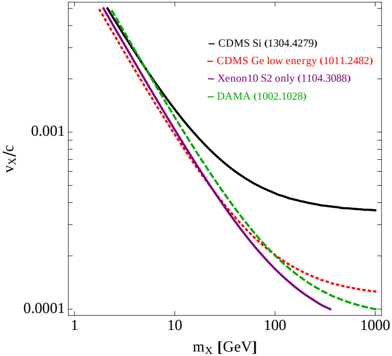
Cylindrical cow: model DDM velocity distribution as rotational + Maxwellian, with dispersion set by cooling

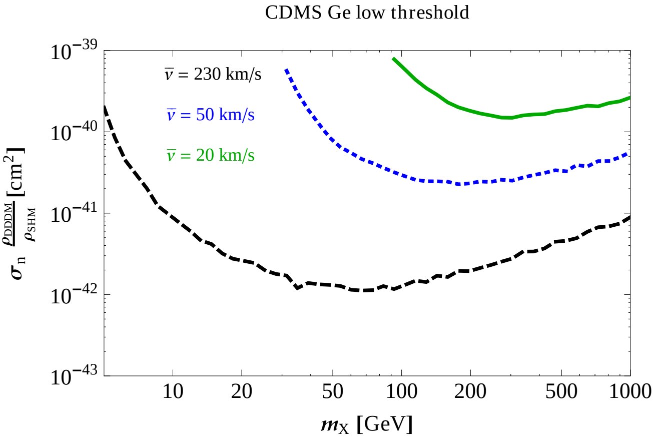
Direct detection

- Cooled DM reduces available kinetic energy for DM-nucleon scattering
- For a given energy threshold E_{thr}, experiment is only sensitive to $v_{DM}^2 > \frac{E_{thr} m_N}{2\mu^2}$



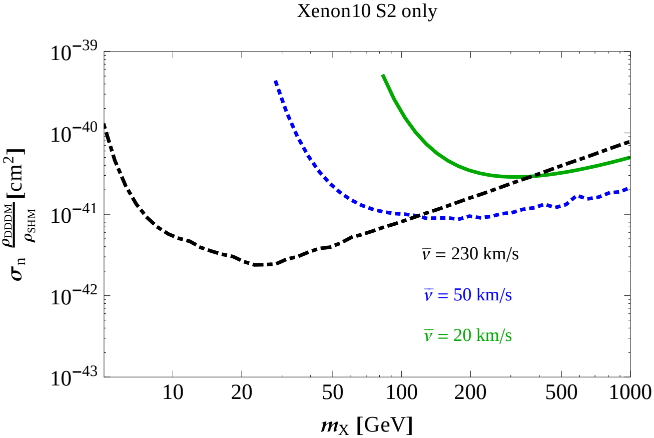
(See also: Fox, Liu, Weiner; Fox, Kribs, Tait; McCollough, Randall)

Direct detection



Bounds from CDMS-Ge low threshhold analysis assuming Maxwellian halo

Direct detection



Bounds from XENON10 S2 analysis assuming Maxwellian halo

Indirect detection: solar capture

Usual story of solar capture:

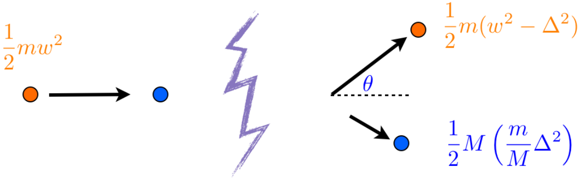
- Captured DM in massive bodies:

$$\frac{dN}{dt} = C_N - C_A N^2$$

- Steady state abundance $N_{eq} = \sqrt{\frac{C_N}{C_A}}$
- $\Rightarrow$ Annihilation rate $\Gamma_A = C_N$ simply related to nuclear cross-section, mass
- Signal: localized neutrino flux (spectrum dependent on annihilation mode)

Capture of dark matter

Capture rates:



- Capture: $w^2 - \Delta^2 < v_{esc}^2(r)$
- Rate at r:
  $\Omega(w) = n_N(r)w \int d\cos\theta \; \sigma(\cos\theta)\Big|_{\Delta^2(\cos\theta) > w^2 - v_{esc}^2(r)}$

Capture of Dark Matter

- Total capture rate depends on
  - velocity distribution outside potential well: $f(u)$
  - capture rate at r: $\Omega(w)$
  - depth of potential well: $w^2 = u^2 + v_{esc}(r)^2$

$$\frac{dC}{du\,dV} = \frac{f(u)}{u}\,w\,\Omega(w)$$

- For constant cross-section σ_N:

$$\Omega(w) = n_N(r)\sigma_N w \left(v_{esc}^2 - \frac{(m_D - m_N)^2}{4 m_D m_N} u^2 \right)$$

- $v_{\odot,esc}(R_\odot) = 618$ km/s

Capture of self-interacting DM

- Additional self-capture process

$$\frac{dN}{dt} = C_N + C_S N - C_A N^2$$

alters simple relation of flux to C_N (Zentner)

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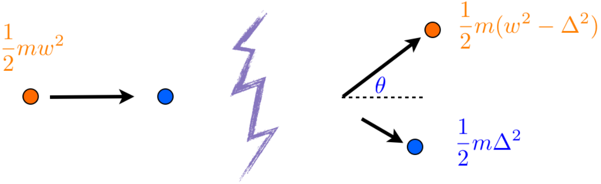
- Velocity dependent self-scattering can lead to strong enhancements

Self-capture and evaporation



- Capture: $w^2 - \Delta^2 < v_{esc}^2(r)$
- Ejection: $\Delta^2 > v_{esc}^2(r)$ (Zentner)

Cross-sections for capture

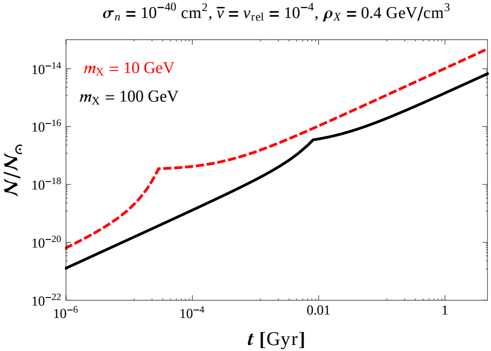
- Rutherford X-$\bar{X}$, X-X scattering cross-section gives enhancement at small angles
- Regulation of *t*-channel singularity:
  - in a single collision: finite scattering angle required for capture
  - integrating over incident DM, by screening: net dark charge neutrality in the sun
  - dark Debye wavelength: $\lambda_D = \sqrt{\frac{T_\odot}{4\pi\alpha_D n_D}}$
- Eventually self-capture saturates, $\langle\sigma_{cap}\rangle N = \pi r_D^2$

Symmetric self-interacting DM

- Solution for self-interacting DM: $N(t) = \frac{C_N \tanh(t/\tau)}{1/\tau - C_S \tanh(t/\tau)}$ with $1/\tau = \sqrt{C_N C_A - C_S^2}$ (Zentner)
- If $C_N \gg C_S$ then largely the same as non-self-interacting
- If $C_S \gg C_N$ then steady-state annihilation rate becomes $\Gamma = \frac{4C_S^2}{C_A}$
- Self-capture can dominate for $\bar{v} \sim 10^{-4}$ if σ_N is not too large

Asymmetric self-interacting DM

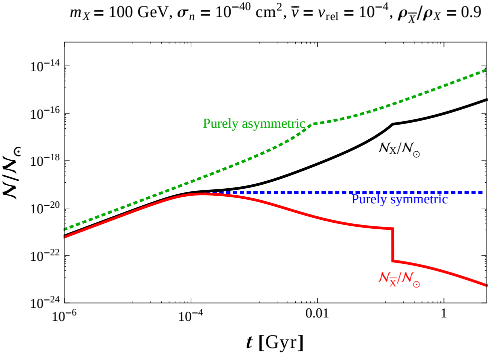
- Asymmetric DM: accumulation without annihilation
- $N(t) = \frac{C_N}{C_S}(e^{C_S t} - 1)$ grows rapidly
  - saturation of self-capture at t_*, linear afterwards



$\sigma_n = 10^{-40}\ \text{cm}^2,\ \bar{v} = v_{\text{rel}} = 10^{-4},\ \rho_X = 0.4\ \text{GeV/cm}^3$

Dissipative DM in the sun

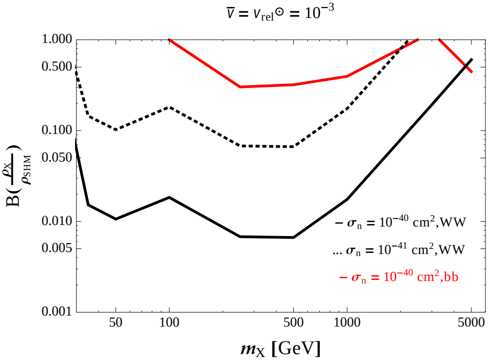
- The general case interpolates:



$m_X = 100$ GeV, $\sigma_n = 10^{-40}$ cm^2, $\bar{v} = v_{\rm rel} = 10^{-4}$, $\rho_{\overline{X}}/\rho_X = 0.9$

Neutrino telescope bounds

- Best bounds from IceCube:



IceCube limits, $\bar{v} = 10^{-3}c$

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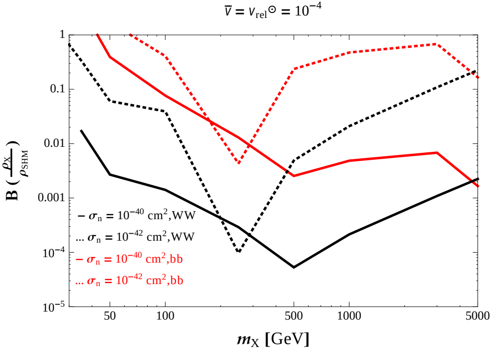


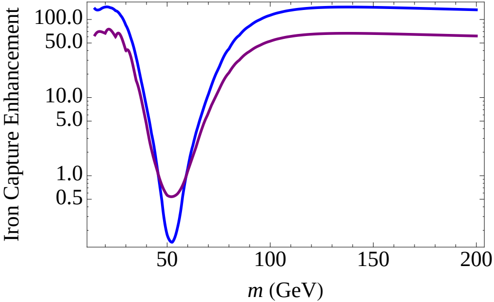
IceCube limits, $\bar{v} = 10^{-4}c$

DM in the Earth

- Additional information from captured DM annihilating in the Earth
- Shallow potential well highly sensitive to cooled velocity dispersions: $v_{esc,\oplus} = 11$ km/s
- Cannot consider in isolation: Earth sits inside Sun's potential well
    - Minimum relative velocity $v_{min} = \sqrt{\frac{2G_N M_\odot}{R_{orb}}} - v_{orb}$

Nuclear capture

- Cooled DM population enhances nuclear capture in Earth:

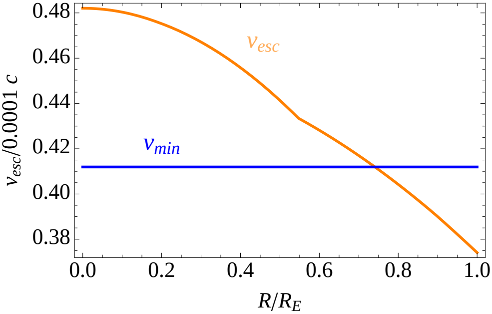


Enhancement of capture rate on iron for $\bar{v} = 10^{-4}c$ relative to $\bar{v} = 10^{-3}c$ (blue) and $\bar{v} = 5 \times 10^{-4}c$ (purple)

(See also: Bruch, Peter, Read, Baudis, Lake)

Self-capture and evaporation

- Since $v_{esc,\oplus} \lesssim v_{min}$, DM self interaction is dominated by ejection of captured DM



- Nuclear capture dominates

Conclusions

- Dissipative dynamics in dark sector an interesting and still open possibility
- Qualitatively distinct predictions for local direct and indirect signals
- Direct detection: cooled DM gives lower energy recoils
  - Z-strength cross-sections still allowed if sufficient cooling
- Solar capture: enhanced for kinematic as well as dynamical reasons
  - Constraints more stringent than from direct detection
- Earth capture: signal becomes observable for cooled DM
  - potentially powerful cross-check of particle and astrophysical properties