Black Holes From Atomic Dark Matter

An Introduction to Dark Molecular Chemistry and DarkKROME

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PPC 2021, May 20, 2021
Based on upcoming papers:

2106.xxxx (Ryan, Gurian, Shandera, Jeong) and 2106.xxxx (Ryan, Shandera)

Background: Dissipative/Atomic Dark Matter

Dissipative Dark Matter: self-interacting dark matter model with dissipative interactions aka inelastic collisions

- Energy loss leads to small-scale structure changes
- Standard Model agnostic - can be completely hidden

"Atomic" dark matter model:

- 2 types of **charged** **fundamental fermions** with $U(1)$ interaction - e_D, p_D, γ_D
- 3 primary parameters: m, M, and α
- Has **hydrogen-like microphysics**: recombination, ionization, bremsstrahlung, chemical reactions, etc.
- No nuclear physics (for now)

(For more see Kaplan et al. 2009, Cyr-Racine & Sigurdson 2013, Rosenberg & Fan 2017, Agrawal et al. 2017)

Application: Dark Black Holes

Buckley & DiFranzo (2018) proposed some atomic dark matter in halos could collapse into compact objects **without** deviating from large scale CDM behavior

Shandera et al. (2018) proposed these compact objects would undergo a **Pop III-like direct collapse**, end up as **subsolar** mass dark black holes, and be **aLIGO detectable**

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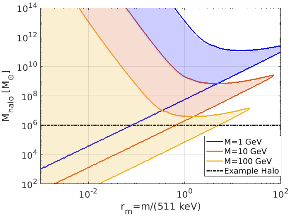
1. Some (but not all) dark halos collapse
2. Collapse dominated by efficient rovibrational cooling
3. Halos sufficiently cool/collapse into subsolar fragments
4. (Future Work) Binary population statistics independent of ADM microphysics/parameters

Including Molecular Chemistry in Halo Collapse

Simple halo collapse test: $t_{\text{cool}} \leq t_{\text{freefall}}$ for small halos, $t_{\text{cool}} > t_{\text{freefall}}$ for large halos (Buckley & DiFranzo Arxiv:1707.03829)

- t_{cool}: time to radiate $O(1)$ kinetic energy
- t_{freefall}: time to collapse by self-gravity



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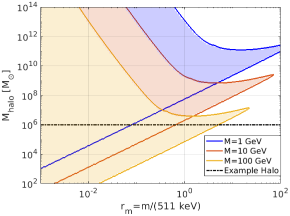

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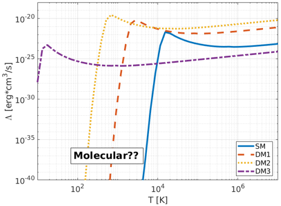
Buckley results are

- Incomplete: need remainder of cooling processes, both atomic (from Rosenberg and Fan 2017) and **molecular**
- Snapshot: assumes chemical equilibrium ≡ static



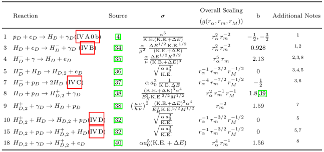
Dark Molecular Chemistry

Problem: Calculating rates from first principals is difficult!

Idea: Use dimensional analysis to rescale known Standard Model results for molecular rates (Ryan, Gurian, Shandera, & Jeong, upcoming)

Rescaled Standard Model Rate:

$$k_{DM}(T) \approx g(r_\alpha, r_m, r_M) \times k_{SM}\left(\frac{T}{r_{\Delta E}}\right)$$



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1	$p_D + e_D \rightarrow H_D + \gamma_D$ (IV A 0 b)	[4]	$\frac{\alpha^5}{K.E.(K.E.+\Delta E)}$	$r_\alpha^2\, r_m^{-2}$	$-\frac{1}{2}, -\frac{3}{2}$	1
3	$H_D + e_D \rightarrow H_D^- + \gamma_D$ (IV B)	[34]	$\frac{\alpha}{\mu^2}\ \frac{\Delta E^{1/2}\, K.E.^{1/2}}{(K.E.+\Delta E)}$	$r_\alpha^2\, r_m^{-2}$	0.928	1, 2
4	$H_D^- + \gamma \rightarrow H_D + e_D$	[35]	$\frac{\alpha}{\mu}\, \frac{\Delta E^{1/2} K^{3/2}}{(K.E.+\Delta E)^3}$	$r_\alpha^5\, r_m$	2.13	2, 3, 8
5	$H_D^- + H_D \rightarrow H_{D,2} + e_D$	[36]	$\sqrt{\frac{\alpha\, a_0^3}{K.E.}}$	$r_\alpha^{-1}\, r_m^{-3/2}\, r_M^{-1/2}$	0	3, 4, 5
7	$H_D^- + p_D \rightarrow 2H_D$ (IV C)	[37]	$\alpha\, a_0^2\, \frac{1}{K.E.\ \Delta E}$	$r_\alpha^{-4}\, r_m^{-7/2}\, r_M^{-1/2}$	$-\frac{1}{2}$	3, 6
8	$H_D + p_D \rightarrow H_{D,2}^+ + \gamma_D$	[38]	$\frac{(K.E.+\Delta E)^3 \alpha^4}{E_H^3 K.E.^{3/2} M^{1/2}}$	$r_\alpha^2\, r_m^{-1}\, r_M^{-1}$	1.8 [39]	
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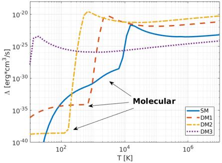

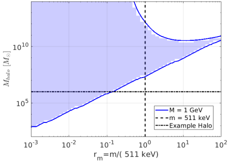

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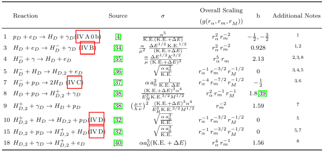

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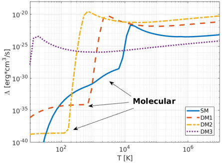
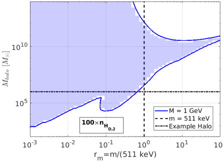




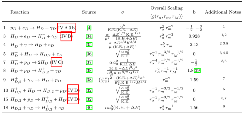
DarkKROME and One Zone Collapse

DarkKROME (Ryan & Shandera 2106.xxxx)

- Extension to KROME software package (`kromepackage.org`)
- Modified to add dark chemistry:
  - ("Atomic") dark sector recognition
  - Atomic reactions and thermal processes (Rosenberg & Fan 2017)
  - Molecular reactions and thermal processes

One Zone Collapse Model

- Uniform density halo evolution model
- Approximation of Population III star formation
- Initial conditions data (Gurian & Jeong, 2106.xxxx)
- Simple thermodynamic and chemical evolution



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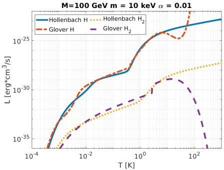

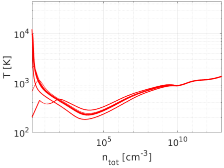

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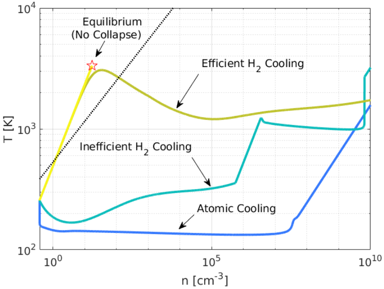
2. Collapse dominated by efficient rovibrational cooling



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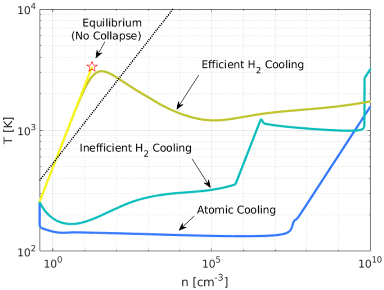
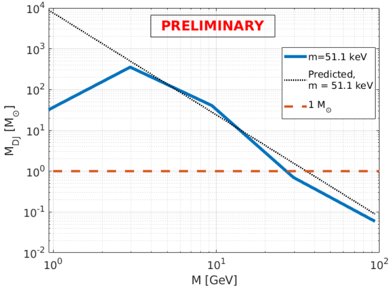
3. Halos sufficiently cool to subsolar mass





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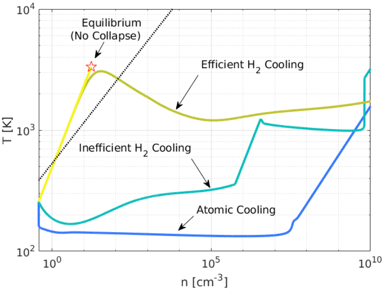
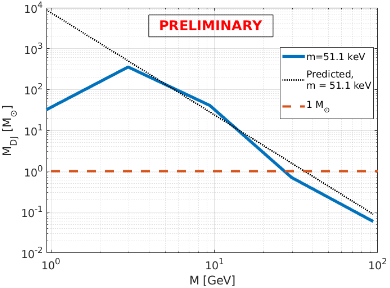
Trajectory generation and analysis ongoing. Expect results soon!





Conclusion

We have developed tools to

- Compute dark molecular process rates by rescaling known Standard Model rates
- Simulate the chemical and thermal evolution of "atomic" dark matter halos

We are using these tools to

- Verify that there are regions of the "atomic" dark matter parameter space where only small halos collapse
- Demonstrate that these halos can cool efficiently, like Pop III star formation
- Demonstrate subsolar-mass dark black hole formation

Still a lot of work to do!

- Add more reactions to dark molecular database
- Run more advanced simulations, e.g. full hydrodynamics
- Extend DarkKROME to other dissipative dark matter models (Chang et al. 2018, Dessert et al. 2019)

Thanks!

Backups

Rescaling Rates

Many process calculations compute the scattering rate, γ:

$$\begin{aligned}\gamma &= \langle \sigma(v)\, v \rangle \\ &= \int_0^\infty \int_0^\infty \sigma(v)\, v\, f(v_1, T_1) f(v_2, T_2) \mathrm{d}v_1 \mathrm{d}v_2\end{aligned}$$

where we have defined

$$f(v_i, T_i) = 4\pi \left(\frac{m_i}{2\pi k_B T_i} \right)^{3/2} v_i^2 \exp\left(-\frac{m_i v_i^2}{2 k_B T_i} \right)$$

Rescaling Rates

After the performing one (interchangeable) integral

$$\gamma = \langle \sigma(v)\, v \rangle$$
$$= \sqrt{\frac{32\, k_B\, T}{\pi\, \mu}} \int_0^\infty \sigma(x^2) \exp\left[-x^2\right] x^3 \mathrm{d}x$$

where we have defined

$$\mu = \frac{m_1 m_2}{m_1 + m_2}, \quad T = \frac{m_1 T_1 + m_2 T_2}{m_1 + m_2}, \quad x^2 = \frac{\text{K.E.}}{k_B T} = \frac{\mu v^2}{2 k_B T}$$

We need to rescale γ but integral makes this messy.

Rescaling Rates

Solution: pull the dimensionality from the integral

Separate dimensionful portion and extract α terms from $\sigma(x)$ (may need to define additional dimensionless variables):

$$\sigma(x^2) = \tilde{R}^2(m, M, \alpha, T)\, \tilde{\sigma}(x^2, y^2, \dots)$$

where we have defined

$$y^2 = \frac{\Delta E}{k_B T}$$

to account for an energy term like the atomic binding energy.

Rescaling Rates

Solution: pull the dimensionality from the integral

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$$\sigma(x^2) = \tilde{R}^2(m, M, \alpha, T)\, \tilde{\sigma}(x^2, y^2, \dots)$$

γ then becomes

$$\gamma \propto \sqrt{\frac{T}{\mu}}\, \tilde{R}^2 \int_0^\infty \tilde{\sigma}(x^2, y^2) \exp[-x^2] x^3 \mathrm{d}x = \sqrt{\frac{T}{\mu}}\, \tilde{R}^2\, f(y^2)$$

Rescaling Rates

Final rescaled rate

Since the $f(y^2)$ term is a pure function of $y^2 = \frac{\Delta E}{k_B T}$, we only need to rescale the thermal factor, $\sqrt{\frac{T}{\mu}}$, and "impact parameter" $\tilde{R}^2$. Furthermore, for the reactions we looked at, $\tilde{R}^2$ could be approximated as product of powers of the various dark parameters and T, giving us the net rescaled rate as

$$\begin{aligned}\gamma_{\mathrm{DM}}(T) &= \left(r_\mu^{-1/2} r_{\Delta E}^{1/2}\right)\left(r_\alpha^{R_\alpha}\, r_m^{R_m}\, r_M^{R_M} r_{\Delta E}^{R_T}\right)\, \gamma_{\mathrm{SM}}\left(\frac{T}{r_{\Delta E}}\right) \\ &= g(r_\alpha, r_m, r_M)\, \gamma_{\mathrm{SM}}(\tilde{T})\end{aligned}$$

Rescaling Rates

Example: Hydrogen Recombination ($p + e \to H +$ photon)

We start with the recombination cross section (using the Milne relation applied to the photoionization cross section):

$$\sigma_{\rm rec}(v) = \left[\frac{g_n}{g_{n+1}}\left(\frac{h\,\nu}{m\,c\,v}\right)^2\right]\left[g_{bf}\,n\frac{64\pi}{\sqrt{27}}\frac{h^2}{\alpha m^2 c^2}\left(\frac{E_{h,0}}{h\,\nu}\right)^3\right]$$
$$\propto \left(\frac{\alpha^5}{T^2}\right)\left(\frac{1}{x^2\,(x^2+y^2)}\right)$$

where we used

$$h\,\nu = \text{K.E.} + E_H = k_B\,T(x^2+y^2), \;\; E_{h,0} \propto m\alpha^2, \;\; \mu \approx m$$

Rescaling Rates

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Then we have

$$\tilde{R}^2 \propto \frac{\alpha^5}{T^2}, \;\; \tilde{\sigma}(x^2, y^2) = \frac{1}{x^2(x^2 + y^2)}.$$

giving

$$g(r_\alpha, r_m, r_M) = \left(r_m^{-1/2} r_{\Delta E}^{1/2}\right)\left(r_\alpha^5 r_{\Delta E}^{-2}\right) = r_\alpha^2 \, r_m^{-2}$$

and

$$\tilde{T} = r_\alpha^{-2} \, r_m^{-1} \, T$$

Rescaling Rates

Example: Hydrogen Recombination ($p + e \to H +$ photon)

So given the Standard Model rate (from Cen 1992)

$$\gamma_{\rm SM}(T) = 8.40 \times 10^{-11}\,\mathrm{cm}^3\,\mathrm{s}^{-1}\,T^{-1/2}\left(\frac{T}{10^3\,\mathrm{K}}\right)^{-0.2}\left(1+\left(\frac{T}{10^6\,\mathrm{K}}\right)^{0.7}\right)^{-1},$$

our rescaled dark rate is

$$\gamma_{\rm DM}(T) = 2.66 \times 10^{-9}\,\mathrm{cm}^3\,\mathrm{s}^{-1}\,[r_\alpha^2\, r_m^{-2}]\left(\frac{T/r_\alpha^2\, r_m}{10^3\,\mathrm{K}}\right)^{-0.7}\left(1+\left(\frac{T/r_\alpha^2\, r_m}{10^6\,\mathrm{K}}\right)^{0.7}\right)^{-1}$$

$$\approx 2.66 \times 10^{-9}\,\mathrm{cm}^3\,\mathrm{s}^{-1}\,[r_\alpha^{3.4}\, r_m^{-1.3}]\left(\frac{T}{10^3\,\mathrm{K}}\right)^{-0.7} \qquad (T \ll 10^6\,\mathrm{K})$$

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