

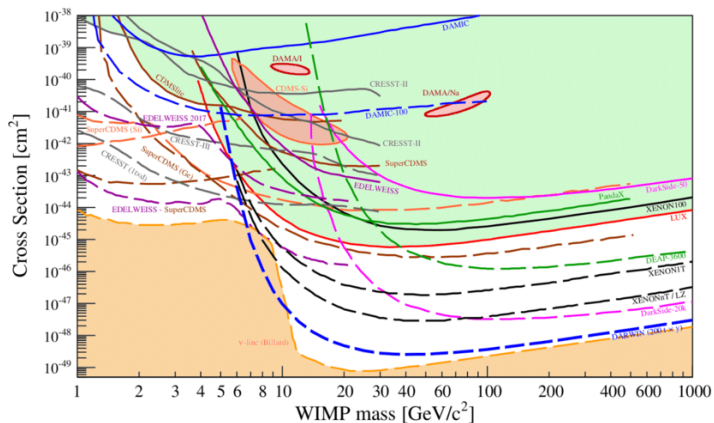
# Dark Molecular Cosmology

James Gurian

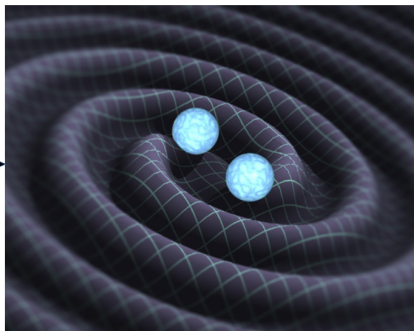
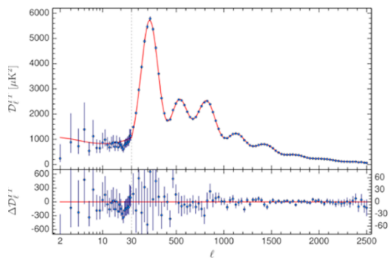
Penn State University

January 27, 2023

# Where's the dark universe?



# Dark matter must have mass



We *infer* the existence of DM from gravitational effects. But now we can “see” gravity directly!

# One simple model: atomic dark matter

We have:

- heavy fermion (dark proton, mass  $M$ )
- light fermion (dark electron, mass  $m$ )
- coupled by dark photon (haha, coupling constant  $\alpha$ ), forming bound states, “dark hydrogen”
- temperature  $T_D/T_{CMB} = \xi$

but we refer mostly to the ratios to standard model value  $r_m, r_M, r_\alpha$ .  
We have the Chandrasekhar mass  $M_{c,D} \sim M_P^3/M^2!$

# aDM can be all of the DM!

Atomic dark matter **can** constitute all of the DM (if  $\xi \ll 1$ ).

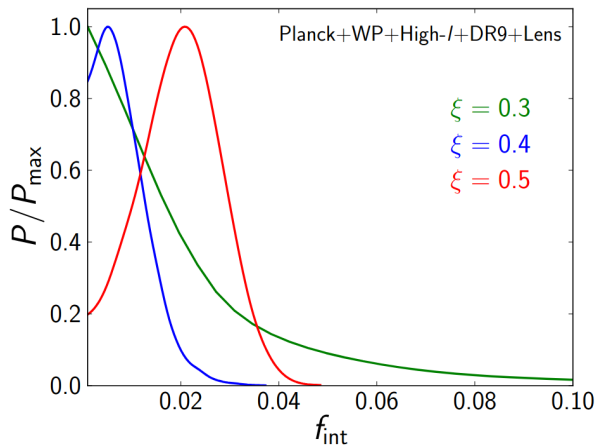
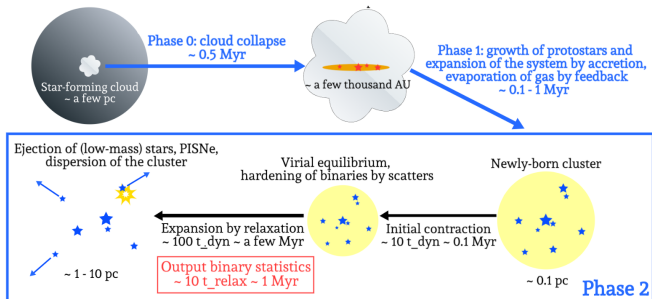


Figure: Cyr-Racine 2014

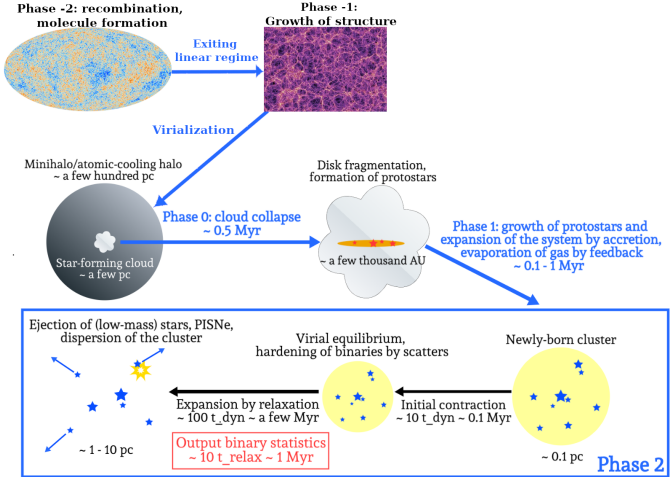
# Roadmap

We need an accurate forward model! Figure: Liu 2020



# Roadmap

We need an accurate forward model!



# Prelim: Dark Molecular Chemistry (Ryan, Gurian, Shandera, Jeong. 2021)

# Non-equilibrium Chemistry

**Table 1.** REACTION RATES FOR HYDROGEN SPECIES

reaction	rate (cm <sup>3</sup> s <sup>-1</sup> or s <sup>-1</sup> )	notes	reference
H1) $\text{H}^+ + \text{e} \rightarrow \text{H} + \gamma$	$R_{e2}$	see text	
H2) $\text{H} + \gamma \rightarrow \text{H}^+ + \text{e}$	$R_{2e}$	see text	
H3) $\text{H} + \text{e} \rightarrow \text{H}^- + \gamma$	$1.4 \times 10^{-18} T_{\text{e}}^{0.928} \exp\left(-\frac{T_{\text{e}}}{16200}\right)$	fit	DJ
H4) $\text{H}^- + \gamma \rightarrow \text{H} + \text{e}$	$1.1 \times 10^{-1} T_{\text{e}}^{2.13} \exp\left(-\frac{8823}{T_{\text{e}}}\right)$	fit	DJ
H5) $\text{H}^- + \text{H} \rightarrow \text{H}_2 + \text{e}$	$1.5 \times 10^{-9}$	$T_{\text{e}} \leq 300$	
	$4.0 \times 10^{-9} T_{\text{e}}^{-0.17}$	$T_{\text{e}} > 300$ , fit	LDZ
H6) $\text{H}^- + \text{H}^+ \rightarrow \text{H}_2^+ + \text{e}$	$6.9 \times 10^{-9} T_{\text{e}}^{-0.35}$	$T_{\text{e}} \leq 8000$	
	$9.6 \times 10^{-7} T_{\text{e}}^{-0.9}$	$T_{\text{e}} > 8000$ , fit	Po
H7) $\text{H}^- + \text{H}^+ \rightarrow 2\text{H}$	$5.7 \times 10^{-6} T_{\text{e}}^{-0.5} + 6.3 \times 10^{-8}$		
	$9.2 \times 10^{-11} T_{\text{e}}^{0.5} + 4.4 \times 10^{-13} T_{\text{e}}$	fit by PAMS	MAP
H8) $\text{H} + \text{H}^+ \rightarrow \text{H}_2^+ + \gamma$	$\text{dex}[-19.38 - 1.523 \log T_{\text{e}} + 1.118(\log T_{\text{e}})^2 - 0.1269(\log T_{\text{e}})^3]$	$1 \leq T_{\text{e}} \leq 32000$ , fit	RP, SBD
H9) $\text{H}_2^+ + \gamma \rightarrow \text{H} + \text{H}^+$	$2.0 \times 10^1 T_{\text{e}}^{2.59} \exp\left(-\frac{82000}{T_{\text{e}}}\right)$	$v = 0$ , fit	Du
	$1.63 \times 10^7 \exp\left(-\frac{32400}{T_{\text{e}}}\right)$	LTE, fit	Ar, St
H10) $\text{H}_2^+ + \text{H} \rightarrow \text{H}_2 + \text{H}^+$	$6.4 \times 10^{-10}$		KAH
H11) $\text{H}_2^+ + \text{e} \rightarrow 2\text{H}$	$2.0 \times 10^{-7} T_{\text{e}}^{-0.5}$	$v = 0$ , fit	SDGR
H12) $\text{H}_2^+ + \gamma \rightarrow 2\text{H}^+ + \text{e}$	$9.0 \times 10^1 T_{\text{e}}^{1.48} \exp\left(-\frac{335000}{T_{\text{e}}}\right)$	fit	BO
H13) $\text{H}_2^+ + \text{H}_2 \rightarrow \text{H}_3^+ + \text{H}$	$2.0 \times 10^{-9}$		TH
H14) $\text{H}_2^+ + \text{H} \rightarrow \text{H}_3^+ + \gamma$	irrelevant		KH
H15) $\text{H}_2 + \text{H}^+ \rightarrow \text{H}_2^+ + \text{H}$	$3.0 \times 10^{-10} \exp\left(-\frac{21050}{T_{\text{e}}}\right)$	$T_{\text{e}} \leq 10^4$ , fit	
	$1.5 \times 10^{-10} \exp\left(-\frac{14000}{T_{\text{e}}}\right)$	$T_{\text{e}} > 10^4$ , fit	HMF
H16) $\text{H}_2 + \text{e} \rightarrow \text{H} + \text{H}^-$	$2.7 \times 10^{-8} T_{\text{e}}^{-1.27} \exp\left(-\frac{43000}{T_{\text{e}}}\right)$	$v = 0$ , fit	SA
H17) $\text{H}_2 + \text{e} \rightarrow 2\text{H} + \text{e}$	$4.4 \times 10^{-10} T_{\text{e}}^{0.35} \exp\left(-\frac{102000}{T_{\text{e}}}\right)$	fit by MD	Co
H18) $\text{H}_2 + \gamma \rightarrow \text{H}_2^+ + \text{e}$	$2.9 \times 10^2 T_{\text{e}}^{1.56} \exp\left(-\frac{178500}{T_{\text{e}}}\right)$	fit	OR
H19) $\text{H}_3^+ + \text{H} \rightarrow \text{H}_2^+ + \text{H}_2$	$7.7 \times 10^{-9} \exp\left(-\frac{17560}{T_{\text{e}}}\right)$	fit	SMT
H20) $\text{H}_3^+ + \text{e} \rightarrow \text{H}_2 + \text{H}$	$4.6 \times 10^{-6} T_{\text{e}}^{-0.65}$		Su
H21) $\text{H}_2 + \text{H}^+ \rightarrow \text{H}_3^+ + \gamma$	$1.0 \times 10^{-16}$		GH
H22) $\text{H}_3^+ + \gamma \rightarrow \text{H}_2^+ + \text{H}$	irrelevant		KH

(Galli and Palla 1998)

Plus molecular cooling rates!

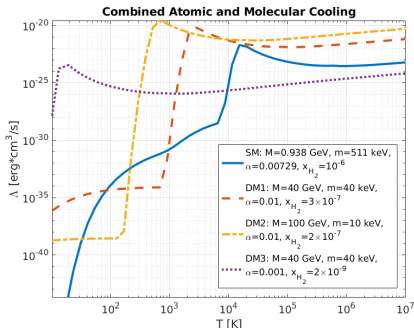
# Re-scaling

$$E_H \propto r_m r_\alpha^2$$

$$\sigma_{T,D} \propto r_\alpha^2 r_m^{-2}$$

$$\gamma_D(T) = g(r_\alpha, r_m, r_M) \gamma_{SM}(T/r_{\Delta E})$$

See Ryan 2021, Rosenberg 2017, and Hart 2017 for details!



## Rescaling: Results

#	Reaction	$\sigma$	Re-scaling pre-factor
1	$p + e \rightarrow H + \gamma$	$\frac{\alpha^5}{\text{K.E.}(\text{K.E.} + \Delta E)}$	$r_\alpha^2 r_m^{-2}$
2	$H + \gamma \rightarrow p + e$	$\mu \alpha^5 \frac{1}{(\text{K.E.} + \Delta E)^3}$	$r_\alpha^5 r_m$
3	$H + e \rightarrow H^- + \gamma$	$\frac{\alpha}{\mu^2} \frac{\Delta E^{1/2} \text{K.E.}^{1/2}}{(\text{K.E.} + \Delta E)}$	$r_\alpha^2 r_m^{-2}$
4	$H^- + \gamma \rightarrow H + e$	$\frac{\alpha}{\mu} \frac{\Delta E^{1/2} K^{3/2}}{(\text{K.E.} + \Delta E)^3}$	$r_\alpha^5 r_m$
5	$H^- + H \rightarrow H_2 + e$	$\sqrt{\frac{\alpha a_0^3}{\text{K.E.}}}$	$r_\alpha^{-1} r_m^{-3/2} r_M^{-1/2}$
7	$H^- + p \rightarrow 2H$	$\alpha a_0^2 \sqrt{\mu} \frac{\sqrt{\text{K.E.} + \Delta E}}{\text{K.E.} \Delta E}$	$r_\alpha^{-3} r_m^{-3}$
8	$H + p \rightarrow H_2^+ + \gamma$	$\frac{(\text{K.E.} + \Delta E)^3 \alpha^4}{E_H^3 \text{K.E.}^{3/2} M^{1/2}}$	
9	$H_2^+ + \gamma \rightarrow H + p$	$\left(\frac{\mu v}{h\nu}\right)^2 \frac{(\text{K.E.} + \Delta E)^3 \alpha^4}{E_H^3 \text{K.E.}^{3/2} M^{1/2}}$	$r_\alpha^5 r_m^{1/2} r_M^{1/2}$
10	$H_2^+ + H \rightarrow H_2 + p$	$\sqrt{\frac{\alpha a_0^3}{\text{K.E.}}}$	$r_\alpha^{-1} r_m^{-3/2} r_M^{-1/2}$
13	$H_2^+ + H_2 \rightarrow H_3^+ + H$	— " —	— " —
15	$H_2 + p \rightarrow H_2^+ + H$	— " —	— " —
20	$H_3^+ + e \rightarrow H + H_2$	$\frac{\alpha a_0}{\text{K.E.}}$	$r_\alpha^{-1} r_m^{-2} r_M$
*	$H_2 + H \rightarrow 3H$	$a_0^2$	$r_\alpha^{-1} r_m^{-3/2} r_M^{-1/2}$
3B1	$3H \rightarrow H_2 + H$	$a_0^2 \left[ \frac{n_{H_2}}{n_H^2} \right]_{\text{LTE}}$	$r_\alpha^{-4} r_m^{-4} r_M^{-1}$
3B2	$H_2 + 2H \rightarrow 2H_2$	— " —	— " —
3B3	$2H + H^+ \rightarrow H_2 + H^+$	— " —	— " —
3B4	$2H + H^+ \rightarrow H_2^+ + H$	— " —	— " —

# Phase –2: Recombination and Molecule Formation

Gurian, Jeong, Ryan, Shandera. 2021

# Primordial Molecules

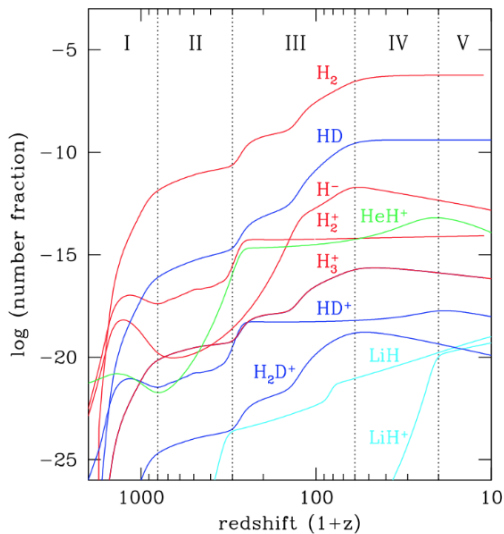
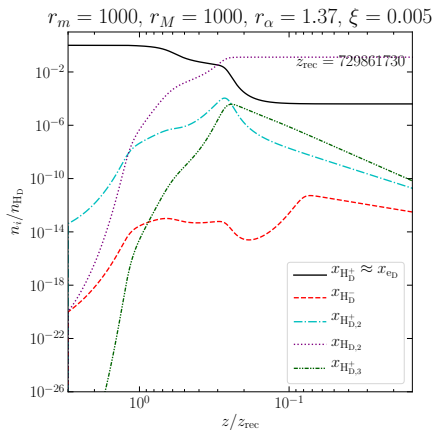
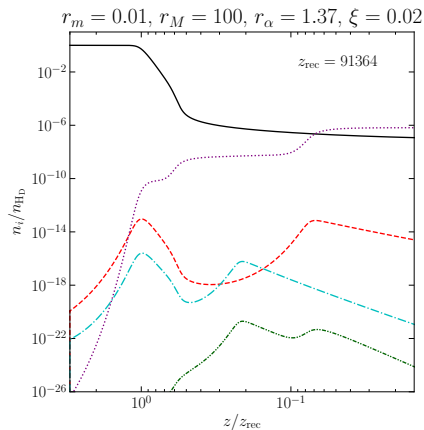


Figure: Galli and Palla 2012

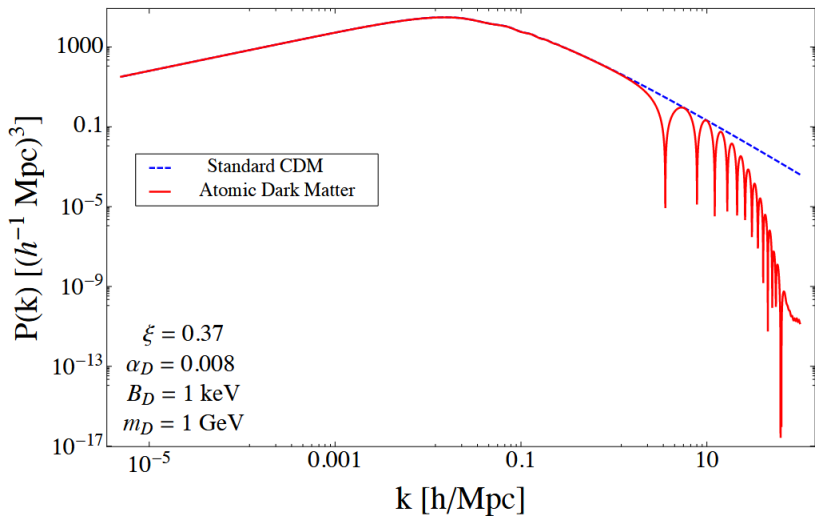
## Abundance Results

[github.com/jamesgurian/RecfastJulia](https://github.com/jamesgurian/RecfastJulia)



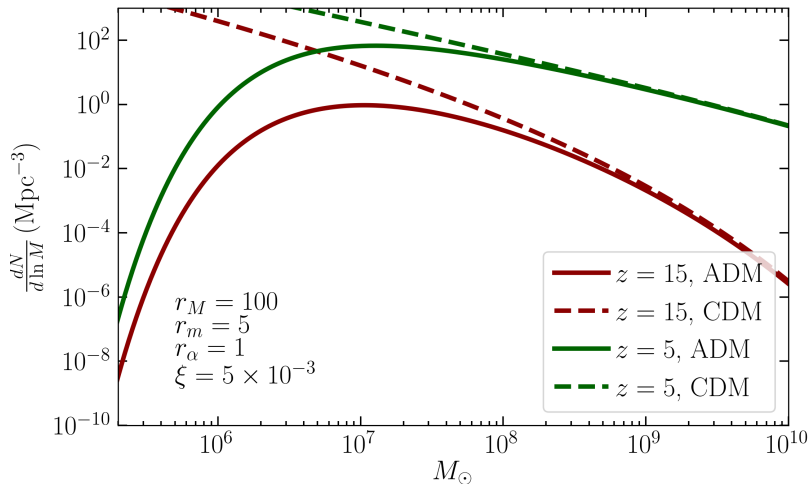
# Phase -1: Linear Power Spectrum to Structure Formation

## DAO and Diffusion

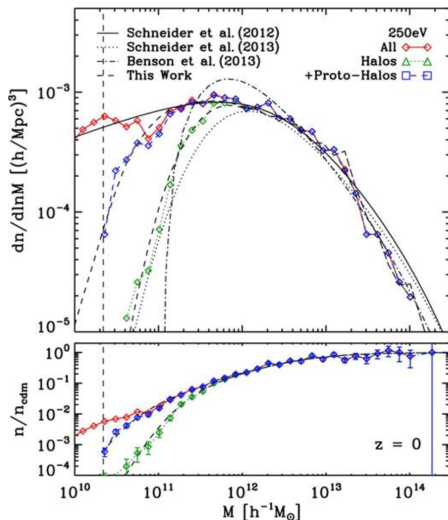


Cyr-Racine 2013

## Halo Mass Function



## Halo(?) Mass Function



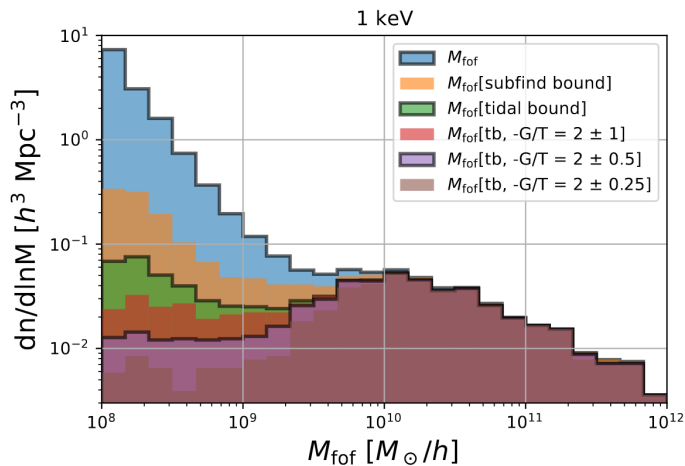
(Stucker 2021)

# Halo(?) Mass Function

but agree reasonably well in the CDM case. Although this may, in part, be because most halo finders have been tested and tuned using CDM simulations, WDM objects in the strongly suppressed regime of the mass function are very different in nature from the clearly bound, nearly spherical quasi-equilibrium haloes that dominate the CDM mass function at all masses. As a result, in the WDM case the halo mass function at low mass depends strongly on the definition of a halo; Figure 7 should be understood as an indication

(Stucker 2021)

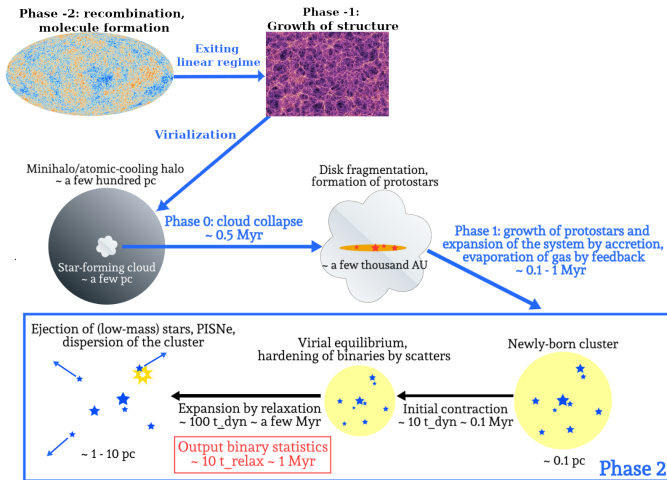
## Halo(?) Mass Function



(Stucker 2021)

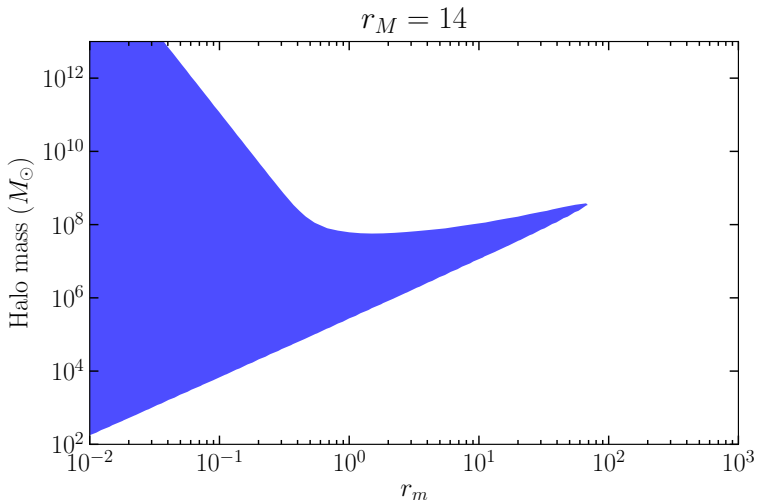
## Halos to stars

## Gas collapses in DM overdensities



## Effects from dissipation

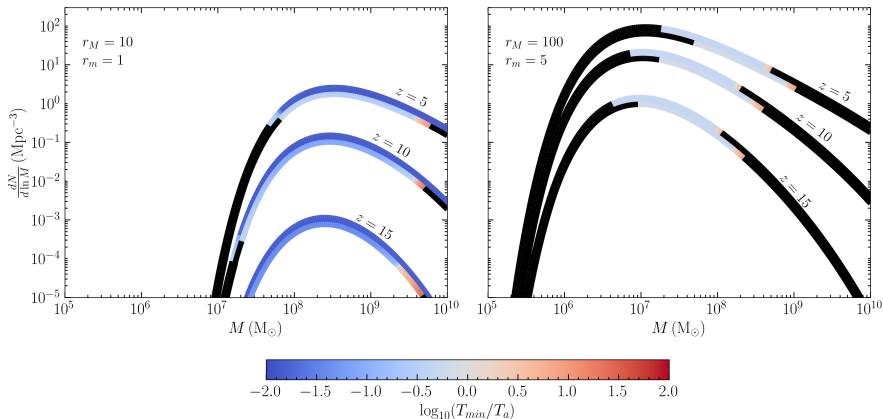
Some halos cool: if  $t_c < t_{ff}$ , collapse can occur (Buckley+ 2018)



## Improvement: Solve the Chemical Network

#	Reaction	$\sigma$	Re-scaling pre-factor
1	$p + e \rightarrow H + \gamma$	$\frac{\alpha^5}{\text{K.E.}(\text{K.E.} + \Delta E)}$	$r_\alpha^2 r_m^{-2}$
2	$H + \gamma \rightarrow p + e$	$\mu \alpha^5 \frac{1}{(\text{K.E.} + \Delta E)^3}$	$r_\alpha^5 r_m$
3	$H + e \rightarrow H^- + \gamma$	$\frac{\alpha}{\mu^2} \frac{\Delta E^{1/2} \text{K.E.}^{1/2}}{(\text{K.E.} + \Delta E)}$	$r_\alpha^2 r_m^{-2}$
4	$H^- + \gamma \rightarrow H + e$	$\frac{\alpha}{\mu} \frac{\Delta E^{1/2} \text{K}^{3/2}}{(\text{K.E.} + \Delta E)^3}$	$r_\alpha^5 r_m$
5	$H^- + H \rightarrow H_2 + e$	$\sqrt{\frac{\alpha a_0^3}{\text{K.E.}}}$	$r_\alpha^{-1} r_m^{-3/2} r_M^{-1/2}$
7	$H^- + p \rightarrow 2H$	$\alpha a_0^2 \sqrt{\mu} \frac{\sqrt{\text{K.E.} + \Delta E}}{\text{K.E.} \Delta E}$	$r_\alpha^{-3} r_m^{-3}$
8	$H + p \rightarrow H_2^+ + \gamma$	$\frac{(\text{K.E.} + \Delta E)^3 \alpha^4}{E_H^3 \text{K.E.}^{3/2} M^{1/2}}$	
9	$H_2^+ + \gamma \rightarrow H + p$	$\left(\frac{\mu v}{h \nu}\right)^2 \frac{(\text{K.E.} + \Delta E)^3 \alpha^4}{E_H^3 \text{K.E.}^{3/2} M^{1/2}}$	$r_\alpha^5 r_m^{1/2} r_M^{1/2}$
10	$H_2^+ + H \rightarrow H_2 + p$	$\sqrt{\frac{\alpha a_0^3}{\text{K.E.}}}$	$r_\alpha^{-1} r_m^{-3/2} r_M^{-1/2}$
13	$H_2^+ + H_2 \rightarrow H_3^+ + H$	—"	—"
15	$H_2 + p \rightarrow H_2^+ + H$	—"	—"
20	$H_3^+ + e \rightarrow H + H_2$	$\frac{\alpha a_0}{\text{K.E.}}$	$r_\alpha^{-1} r_m^{-2} r_M$
*	$H_2 + H \rightarrow 3H$	$a_0^2$	$r_\alpha^{-1} r_m^{-3/2} r_M^{-1/2}$
3B1	$3H \rightarrow H_2 + H$	$a_0^2 \left[ \frac{n_{H_2}}{n_H^2} \right]_{\text{LTE}}$	$r_\alpha^{-4} r_m^{-4} r_M^{-1}$
3B2	$H_2 + 2H \rightarrow 2H_2$	—"	—"
3B3	$2H + H^+ \rightarrow H_2 + H^+$	—"	—"
3B4	$2H + H^+ \rightarrow H_2^+ + H$	—"	—"

## HMF with cooling



# Conclusions

- Gravitational waves can constrain DM microphysics
- aDM can be all of the dark matter, if cold
- We worked out the dark chemistry and you can use our tools! (DarkKROME and RecfastJulia)
- Diffusion damping/DAO and dissipative physics alter halo structure and abundance

# Backup

## Cooling

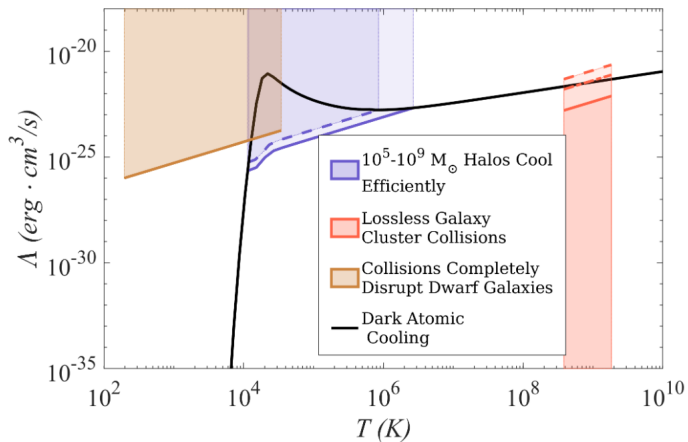


Figure: Singh 2020

## LIGO Rates

$m_X$ [GeV]	$m_c$ [keV]	$M_{\text{Chand.}}^{\text{dark}}$ [ $10^{-5} M_{\odot}$ ]	$M_{\text{DBH}}$ [ $M_{\odot}$ ]	Rates per year				$m_1 < 1.4$	$m_1, m_2 < 1.4$
				raw (MWE $G^{-1}$ )	aLIGO (current)	aLIGO (full)	Einstein T.	[%]	[%]
62	31	33	0.0068 – 0.68	$2.0 \times 10^{-6} (10^{-4})$	0.0012 (0.12)	0.020 (2.0)	60 (6000)	100%	100%
48	47	56	0.016 – 1.6	$1.3 \times 10^{-6} (10^{-4})$	0.0065 (0.65)	0.11 (11)	330 (33k)	99%	79%
32	70	125	0.054 – 5.4	$6.6 \times 10^{-7} (10^{-5})$	0.068 (6.8)	1.1 (110)	3500 (350k)	53%	9.3%
16	140	500	0.43 – 43	$1.9 \times 10^{-7} (10^{-5})$	0.89 (89)	22 (2200)	92k (9200k)	9.8%	0.14%

Table: Shandera 2018

# Molecular Scaling

$$x^2 = \frac{\text{K.E.}}{k_B T} = \frac{\mu v^2}{2 k_B T},$$

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

$$\gamma_{\text{DM,non-}\gamma} = \langle \sigma v \rangle \propto \sqrt{\frac{T}{\mu}} \int_0^\infty \sigma(x; y) x^3 e^{-x^2} dx.$$

$$\gamma_{\text{DM},\gamma}(T_\gamma) = 2c \int_{\Delta E/h}^\infty d\nu \frac{\nu^2 \sigma_{\text{photo}}(\nu)}{e^{h\nu/k_B T_\gamma} - 1}$$

# Three Level Atom

$$\frac{dx_{pD}}{dz} = \frac{(1 + K_{H_D} \Lambda_{H_D} n_{H_D} (1 - x_{pD}))}{H(z)(1+z)(1 + K_{H_D} (\Lambda_{H_D} + \beta_{H_D}) n_{H_D} (1 - x_{pD}))} \\ \times \left( x_{eD} x_{pD} n_{H_D} \alpha_{H_D} - \beta_{H_D} (1 - x_{pD}) e^{-h\nu_{H_D} 2s/kT_M} \right),$$

$$\frac{dT_M}{dz} = \frac{8\sigma_{T,D} a_{R,D} T_R^4}{3H(z)(1+z)mc} \frac{x_{eD}}{1+x_{eD}} (T_M - T_R) + \frac{2T_M}{(1+z)}.$$

# Rate Uncertainty

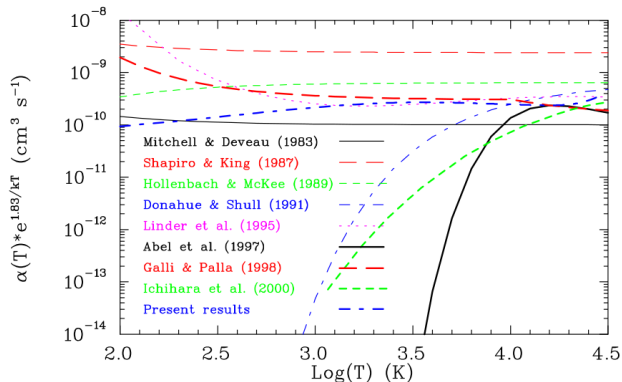


Fig. 1.— Recommended rate coefficients for  $\text{H}_2 + \text{H}^+ \rightarrow \text{H}_2^+ + \text{H}$ . All data have been multiplied by  $\exp(1.83/kT)$  to remove the effects of the 1.83 eV threshold for this process.

Figure: Savin 2004

# DAO and Diffusion

For DM,  $R = \frac{3\bar{\rho}_{DM}}{4\bar{\rho}_{\gamma,D}} \propto \xi^{-4}$ !

$$\frac{1}{k_D^2} = \int_0^\eta \frac{d\tilde{\eta}}{6n_e\sigma_{Ta}(\tilde{\eta})} \left[ \frac{R^2}{(1+R)^2} + \frac{16}{15(1+R)} \right]$$

$$r_{\text{DAO}} = \int_0^{\eta_{\text{dec.}}} d\tilde{\eta} c_s(\tilde{\eta}) = \int_0^{\eta_{\text{dec.}}} d\tilde{\eta} \frac{1}{\sqrt{3(1+R(\tilde{\eta}))}}$$

For the parameters we are studying, (small  $\xi$ ) diffusion wins.

So:  $P(k) \rightarrow P(k)e^{-\left(\frac{k}{k_D}\right)^2}$

# Halo Mass Function

Cutoff in power spectrum (diffusion damping) suppresses halo formation at small scales.

$$\frac{dn}{dM} = \frac{\bar{\rho}}{M^2} \left| \frac{d \ln \sigma}{d \ln M} \right| f(\sigma),$$

Where  $\sigma$  is the RMS density fluctuation and  $f(\sigma)$  is the Sheth-Tormen mass function.