Title: The Minimum Fragment Mass in Dissipative Dark Matter Halos

Speakers: James Gurian

Series: Cosmology & Gravitation

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Abstract: The dark universe may host physics as rich and complex as the visible sector, but the only guaranteed window to the dark sector(s) is through gravity. If the dark matter has a dissipative self-interaction, dark gas can cool and collapse to form compact object whose mergers may be accessible to LIGO. The mass spectrum of the merging compact objects encodes fundamental physical information--a purely gravitational probe of dark matter microphysics.
In this talk, I will present our work to forward-model the gas collapse process in the "atomic dark matter" model, beginning with a retelling of the standard cosmological history including this new ingredient and culminating in a description of the fragmentation scale of the dark gas.

Zoom link: https://pitp.zoom.us/j/99141938599?pwd=T0I1d1A5R0JBNWFlSHlCREl5dElTUT09

The Minimum Fragment Mass In Dissipative Dark Matter Halos

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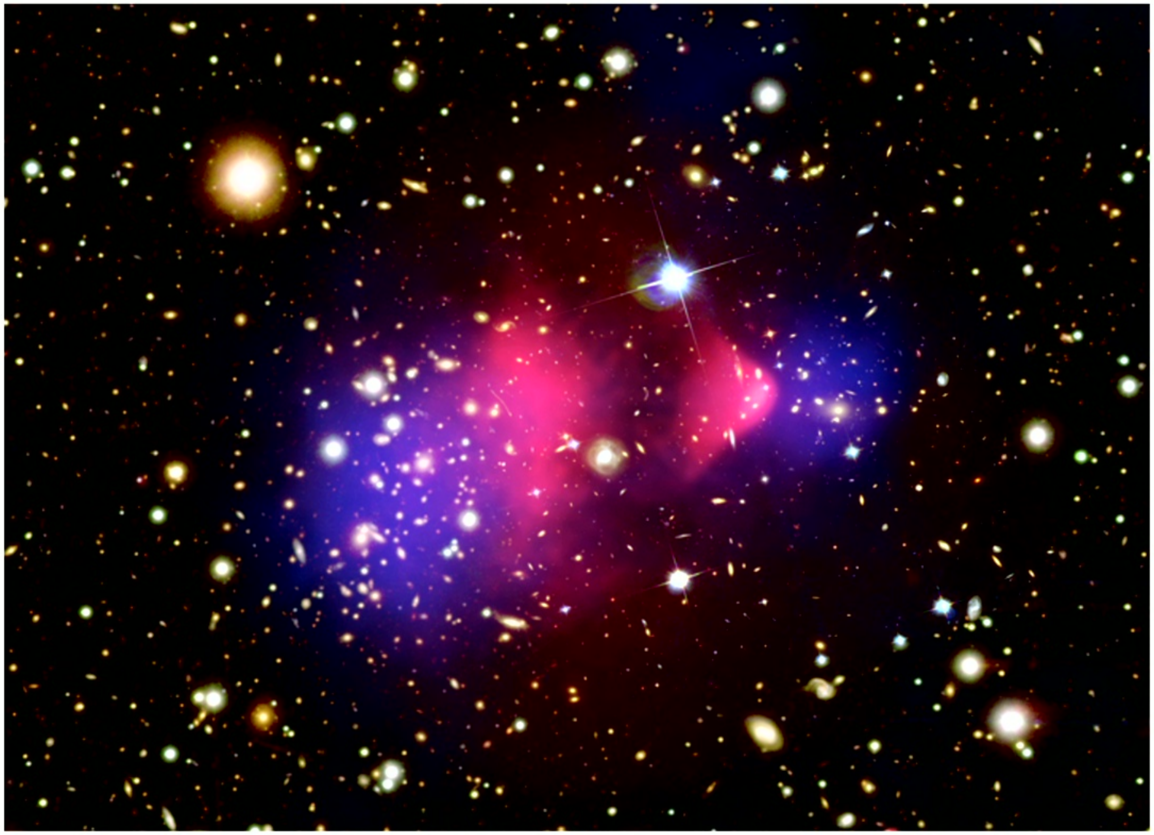
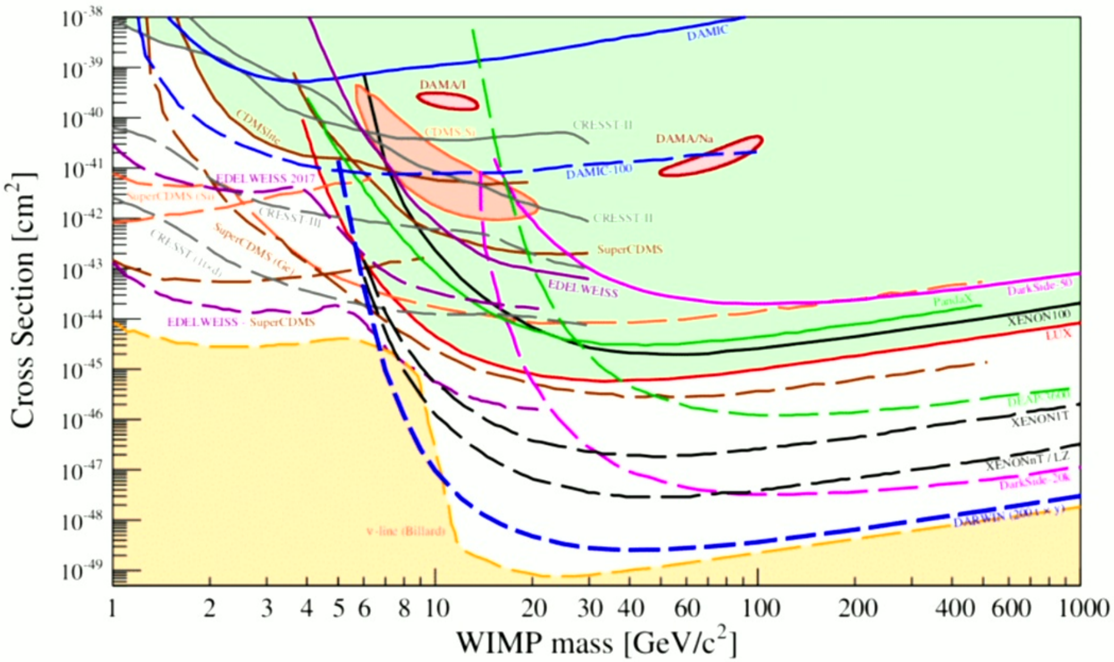
January 16, 2023

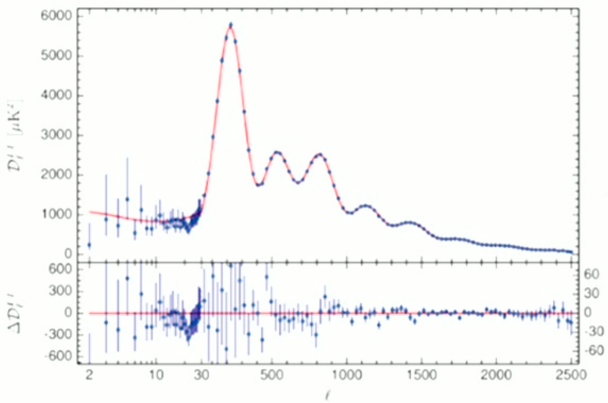
The universe is dark

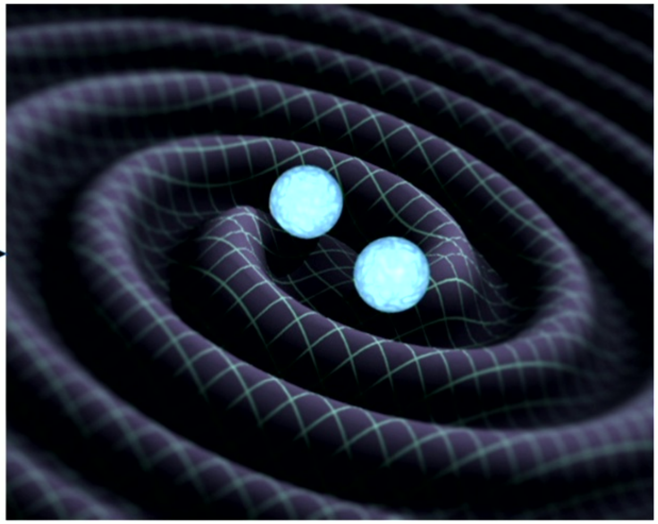


So...where's the dark universe?



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 α), 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_α.
We have the Chandrasekhar mass $M_{c,D} \sim M_P^3/M^2$!

This is testable!

LIGO event rate estimate $\sim 1/\mathrm{yr}$ for $M_{c,D} \sim .01\,\mathrm{M}_\odot$

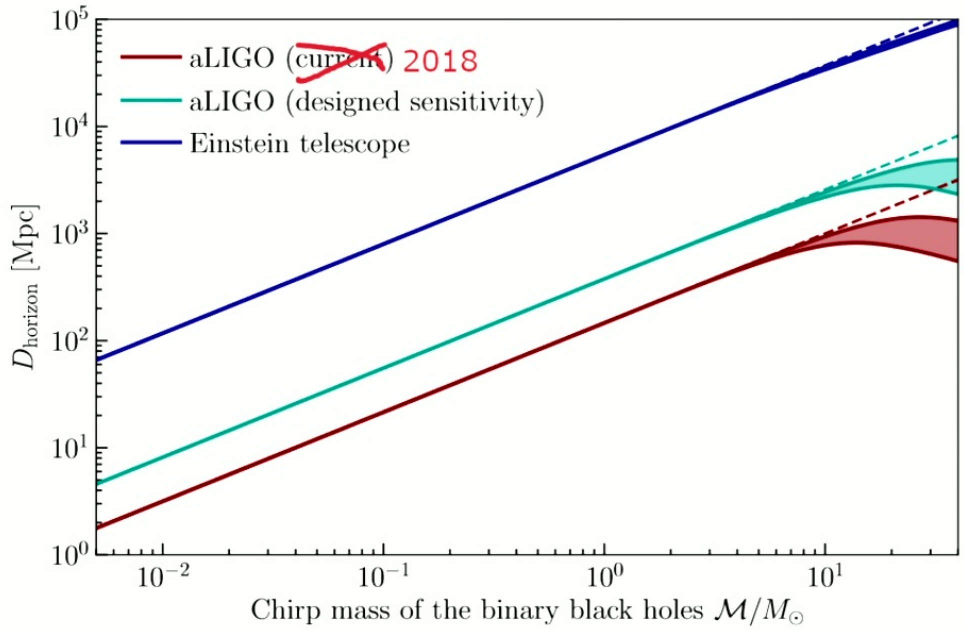


Figure: Shandera 2018.

Two asides

DBH is **not** PBH

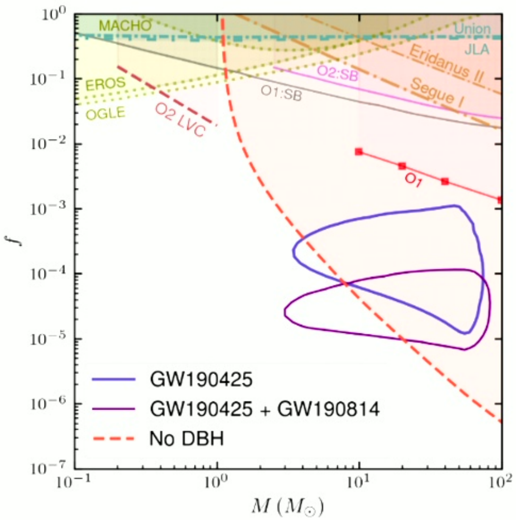


Figure: Singh 2020

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

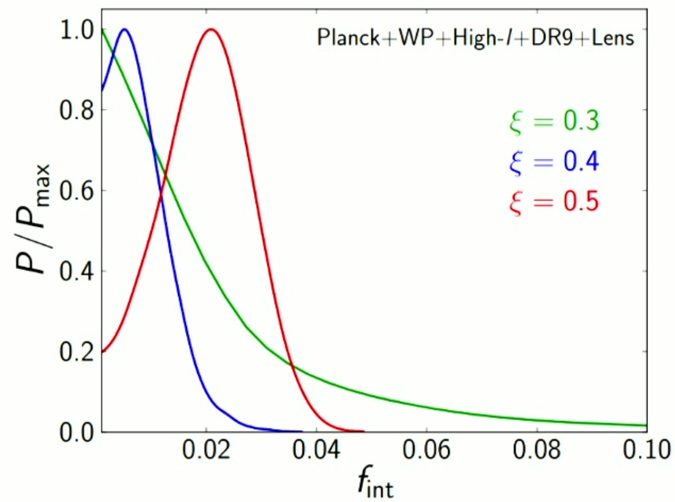
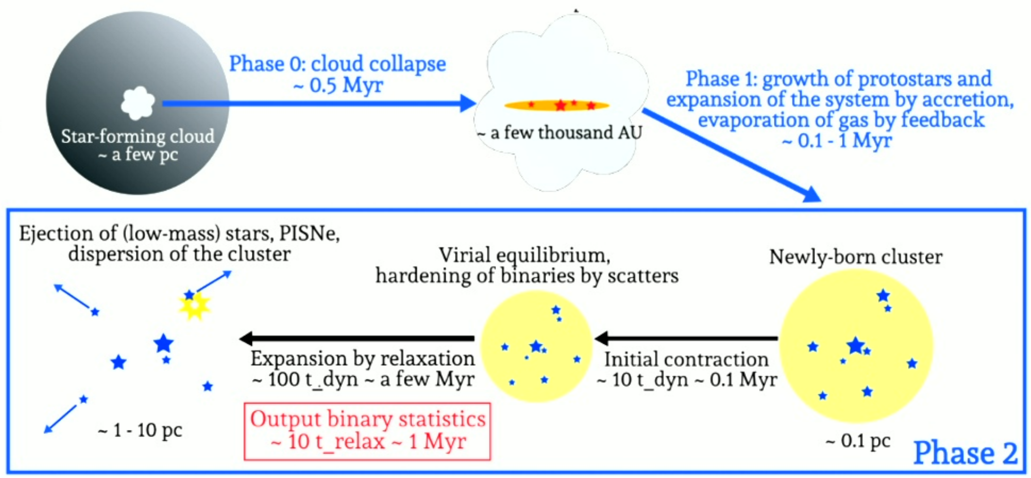


Figure: Cyr-Racine 2014

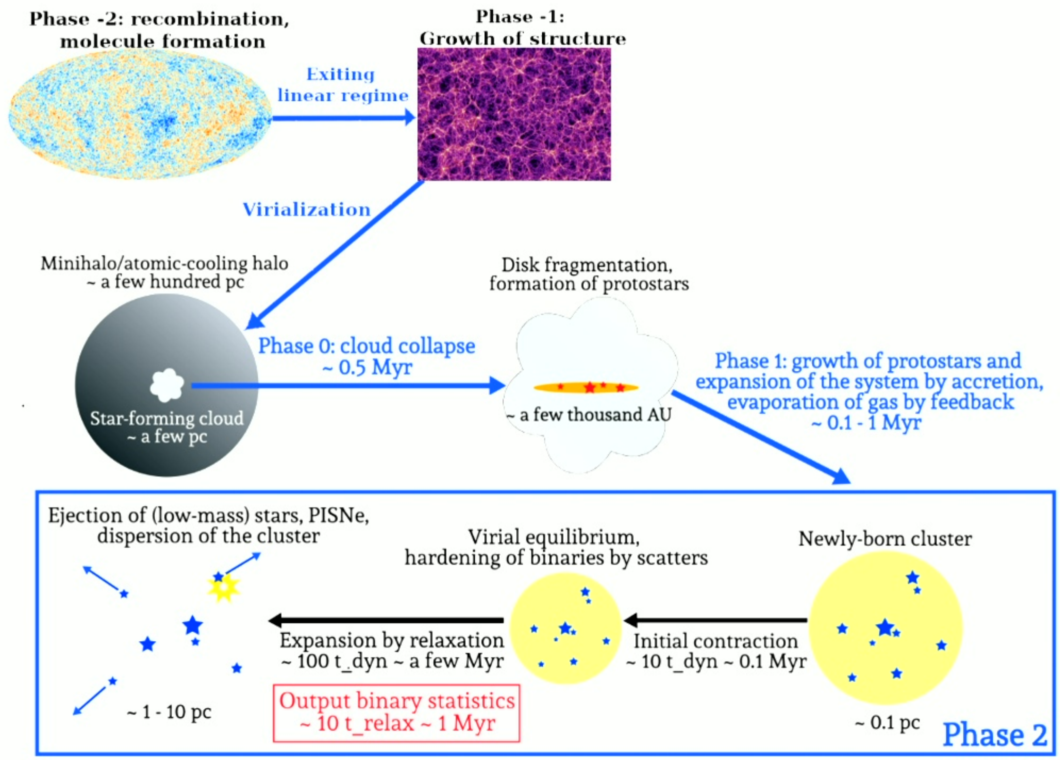
Roadmap

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 ($cm^3\ s^{-1}$ or s^{-1})	notes	reference
H1)	$\mathbf{H^+ + e \rightarrow H + \gamma}$	R_{c2}	see text	
H2)	$\mathbf{H + \gamma \rightarrow H^+ + e}$	R_{2c}	see text	
H3)	$\mathbf{H + e \rightarrow H^- + \gamma}$	$1.4 \times 10^{-18} T_g^{0.928} \exp\left(-\frac{T_g}{16200}\right)$	fit	DJ
H4)	$\mathbf{H^- + \gamma \rightarrow H + e}$	$1.1 \times 10^{-1} T_r^{2.13} \exp\left(-\frac{8823}{T_r}\right)$	fit	DJ
H5)	$\mathbf{H^- + H \rightarrow H_2 + e}$	1.5×10^{-9}	$T_g \leq 300$	
		$4.0 \times 10^{-9} T_g^{-0.17}$	$T_g > 300$, fit	LDZ
H6)	$H^- + H^+ \rightarrow H_2^+ + e$	$6.9 \times 10^{-9} T_g^{-0.35}$	$T_g \leq 8000$	
		$9.6 \times 10^{-7} T_g^{-0.9}$	$T_g > 8000$, fit	Po
H7)	$\mathbf{H^- + H^+ \rightarrow 2H}$	$5.7 \times 10^{-6} T_g^{-0.5} + 6.3 \times 10^{-8} -$		
		$9.2 \times 10^{-11} T_g^{0.5} + 4.4 \times 10^{-13} T_g$	fit by PAMS	MAP
H8)	$\mathbf{H + H^+ \rightarrow H_2^+ + \gamma}$	$\mathrm{dex}[-19.38 - 1.523 \log T_g +$		
		$1.118 (\log T_g)^2 - 0.1269 (\log T_g)^3]$	$1 \leq T_g \leq 32000$, fit	RP, SBD
H9)	$\mathbf{H_2^+ + \gamma \rightarrow H + H^+}$	$2.0 \times 10^1 T_r^{1.59} \exp\left(-\frac{82000}{T_r}\right)$	$v = 0$, fit	Du
		$1.63 \times 10^7 \exp\left(-\frac{32400}{T_r}\right)$	LTE, fit	Ar, St
H10)	$\mathbf{H_2^+ + H \rightarrow H_2 + H^+}$	6.4×10^{-10}		KAH
H11)	$H_2^+ + e \rightarrow 2H$	$2.0 \times 10^{-7} T_g^{-0.5}$	$v = 0$, fit	SDGR
H12)	$H_2^+ + \gamma \rightarrow 2H^+ + e$	$9.0 \times 10^1 T_r^{1.48} \exp\left(-\frac{335000}{T_r}\right)$	fit	BO
H13)	$H_2^+ + H_2 \rightarrow H_3^+ + H$	2.0×10^{-9}		TH
H14)	$H_2^+ + H \rightarrow H_3^+ + \gamma$	irrelevant		KH
H15)	$\mathbf{H_2 + H^+ \rightarrow H_2^+ + H}$	$3.0 \times 10^{-10} \exp\left(-\frac{21050}{T_g}\right)$	$T_g \leq 10^4$, fit	
		$1.5 \times 10^{-10} \exp\left(-\frac{14000}{T_g}\right)$	$T_g > 10^4$, fit	HMF
H16)	$H_2 + e \rightarrow H + H^-$	$2.7 \times 10^{-8} T_g^{-1.27} \exp\left(-\frac{43000}{T_g}\right)$	$v = 0$, fit	SA
H17)	$H_2 + e \rightarrow 2H + e$	$4.4 \times 10^{-10} T_g^{0.35} \exp\left(-\frac{102000}{T_g}\right)$	fit by MD	Co
H18)	$H_2 + \gamma \rightarrow H_2^+ + e$	$2.9 \times 10^2 T_r^{1.56} \exp\left(-\frac{178500}{T_r}\right)$	fit	OR
H19)	$H_3^+ + H \rightarrow H_2^+ + H_2$	$7.7 \times 10^{-9} \exp\left(-\frac{17560}{T_g}\right)$	fit	SMT
H20)	$H_3^+ + e \rightarrow H_2 + H$	$4.6 \times 10^{-6} T_g^{-0.65}$		Su
H21)	$H_2 + H^+ \rightarrow H_3^+ + \gamma$	1.0×10^{-16}		GH
H22)	$H_3^+ + \gamma \rightarrow H_2^+ + H$	irrelevant		KH

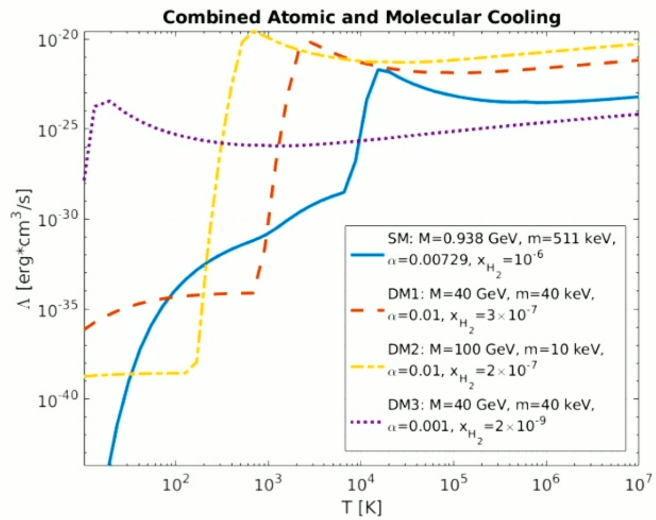
(Galli and Palla 1998)

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	σ	Re-scaling pre-factor
1	$p + e \to \mathrm{H} + \gamma$	$\frac{\alpha^5}{\mathrm{K.E.}(\mathrm{K.E.}+\Delta E)}$	$r_\alpha^2\, r_m^{-2}$
2	$\mathrm{H} + \gamma \to p + e$	$\mu\,\alpha^5 \frac{1}{(\mathrm{K.E.}+\Delta E)^3}$	$r_\alpha^5\, r_m$
3	$\mathrm{H} + e \to \mathrm{H}^- + \gamma$	$\frac{\alpha}{\mu^2}\, \frac{\Delta E^{1/2}\,\mathrm{K.E.}^{1/2}}{(\mathrm{K.E.}+\Delta E)}$	$r_\alpha^2\, r_m^{-2}$
4	$\mathrm{H}^- + \gamma \to \mathrm{H} + e$	$\frac{\alpha}{\mu}\, \frac{\Delta E^{1/2} K^{3/2}}{(\mathrm{K.E.}+\Delta E)^3}$	$r_\alpha^5\, r_m$
5	$\mathrm{H}^- + \mathrm{H} \to \mathrm{H}_2 + e$	$\sqrt{\frac{\alpha\, a_0^3}{\mathrm{K.E.}}}$	$r_\alpha^{-1}\, r_m^{-3/2}\, r_M^{-1/2}$
7	$\mathrm{H}^- + p \to 2\mathrm{H}$	$\alpha\, a_0^2 \sqrt{\mu}\, \frac{\sqrt{\mathrm{K.E.}+\Delta E}}{\mathrm{K.E.}\ \Delta E}$	$r_\alpha^{-3}\, r_m^{-3}$
8	$\mathrm{H} + p \to \mathrm{H}_2^+ + \gamma$	$\frac{(\mathrm{K.E.}+\Delta E)^3 \alpha^4}{E_\mathrm{H}^3 \mathrm{K.E.}^{3/2} M^{1/2}}$	
9	$\mathrm{H}_2^+ + \gamma \to \mathrm{H} + p$	$\left(\frac{\mu\, v}{h\,\nu}\right)^2\, \frac{(\mathrm{K.E.}+\Delta E)^3 \alpha^4}{E_\mathrm{H}^3 \mathrm{K.E.}^{3/2} M^{1/2}}$	$r_\alpha^5\, r_m^{1/2}\, r_M^{1/2}$
10	$\mathrm{H}_2^+ + \mathrm{H} \to \mathrm{H}_2 + p$	$\sqrt{\frac{\alpha\, a_0^3}{\mathrm{K.E.}}}$	$r_\alpha^{-1}\, r_m^{-3/2}\, r_M^{-1/2}$
13	$\mathrm{H}_2^+ + \mathrm{H}_2 \to \mathrm{H}_3^+ + \mathrm{H}$	—"—	—"—
15	$\mathrm{H}_2 + p \to \mathrm{H}_2^+ + \mathrm{H}$	—"—	—"—
20	$\mathrm{H}_3^+ + e \to \mathrm{H} + \mathrm{H}_2$	$\frac{\alpha\, a_0}{\mathrm{K.E.}}$	$r_\alpha^{-1}\, r_m^{-2}\, r_M$
*	$\mathrm{H}_2 + \mathrm{H} \to 3\mathrm{H}$	a_0^2	$r_\alpha^{-1}\, r_m^{-3/2}\, r_M^{-1/2}$
3B1	$3\mathrm{H} \to \mathrm{H}_2 + \mathrm{H}$	$a_0^2 \left[\frac{n_{\mathrm{H}_2}}{n_\mathrm{H}^2}\right]_\mathrm{LTE}$	$r_\alpha^{-4}\, r_m^{-4}\, r_M^{-1}$
3B2	$\mathrm{H}_2 + 2\mathrm{H} \to 2\mathrm{H}_2$	—"—	—"—
3B3	$2\mathrm{H} + \mathrm{H}^+ \to \mathrm{H}_2 + \mathrm{H}^+$	—"—	—"—
3B4	$2\mathrm{H} + \mathrm{H}^+ \to \mathrm{H}_2^+ + \mathrm{H}$	—"—	—"—

Phase −2: Recombination and Molecule Formation

Gurian, Jeong, Ryan, Shandera. 2021

Primordial Molecules

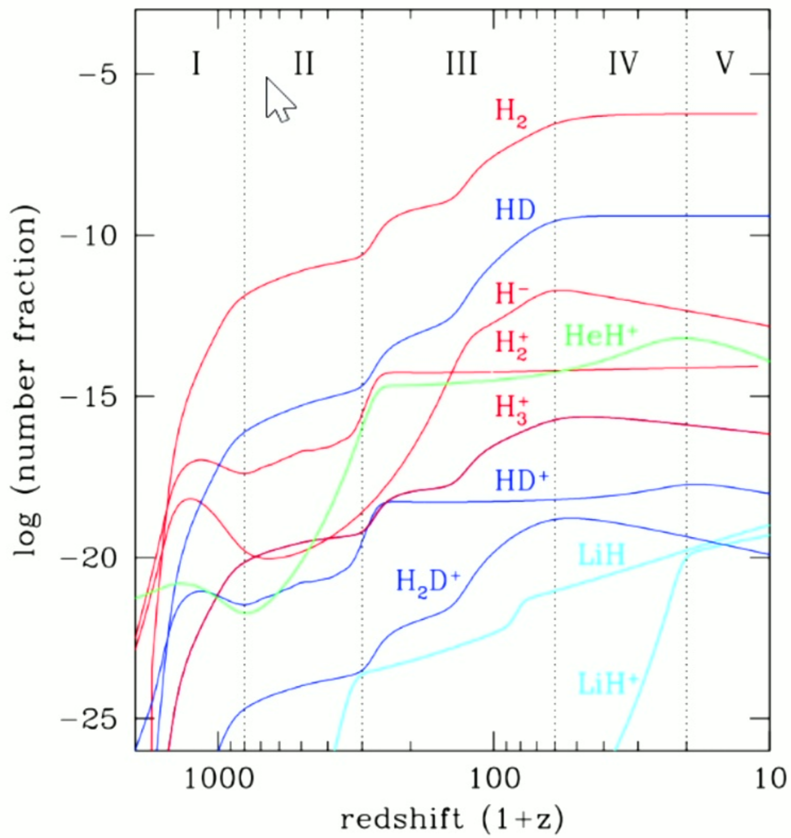
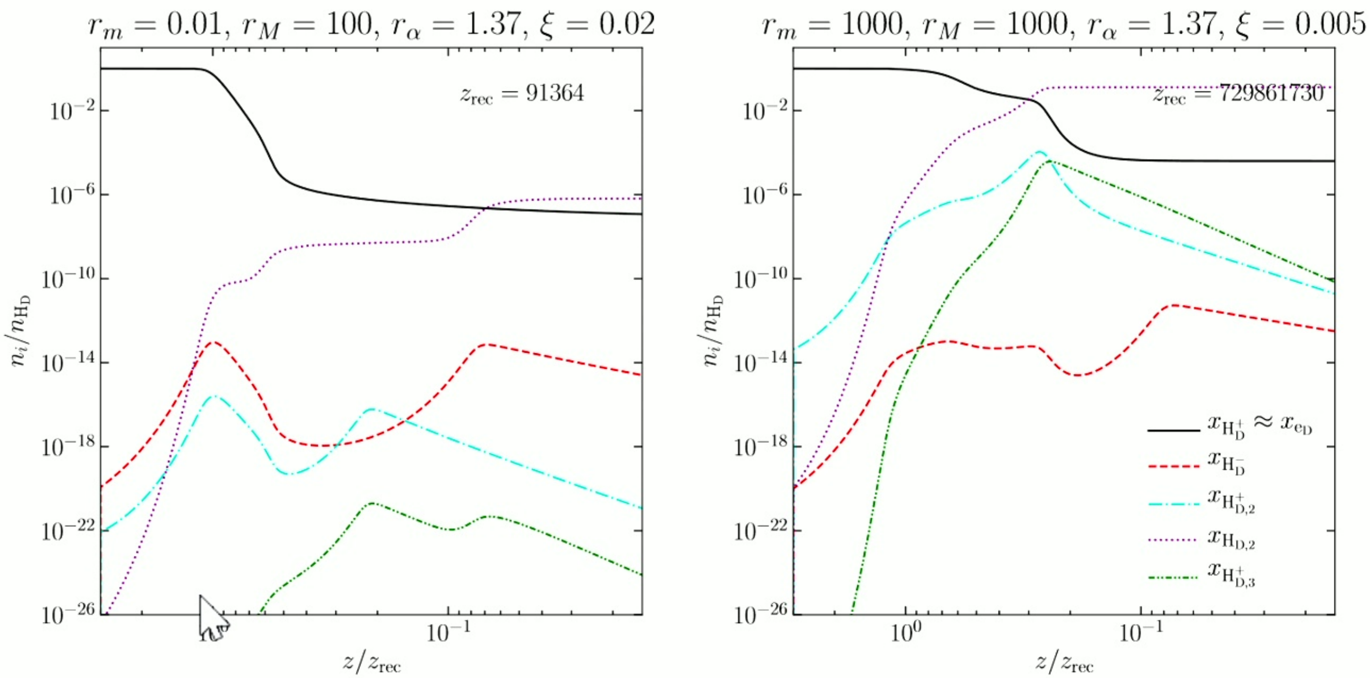


Figure: Galli and Palla 2012

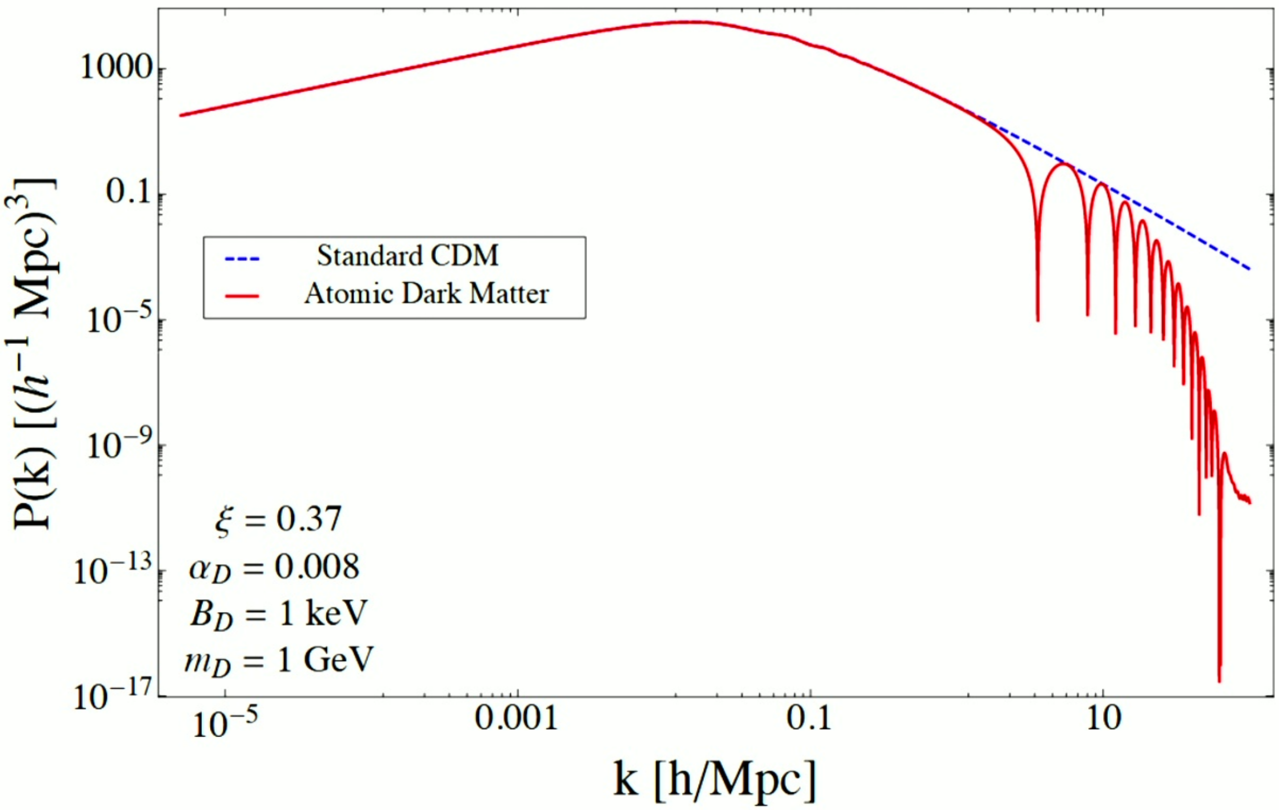
Abundance Results

github.com/jamesgurian/RecfastJulia



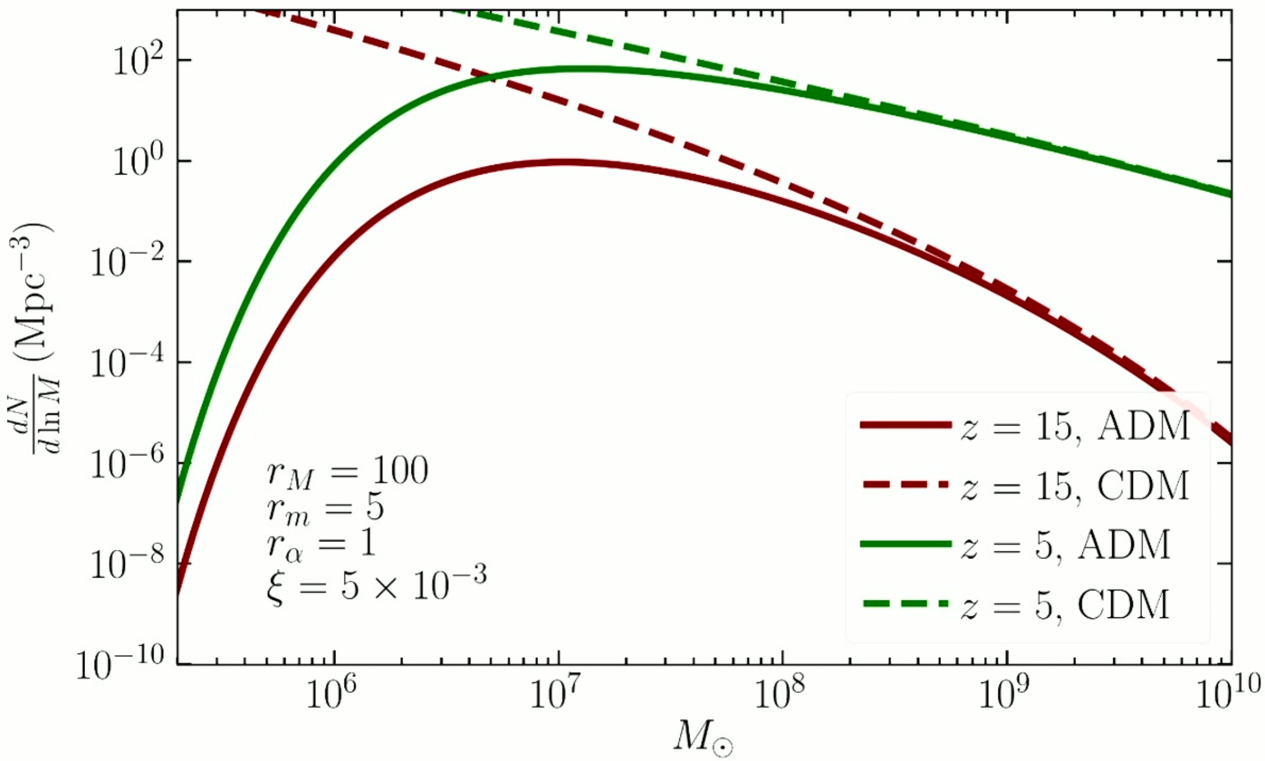
Phase −1: Linear Power Spectrum to Structure Formation

DAO and Diffusion



Cyr-Racine 2013

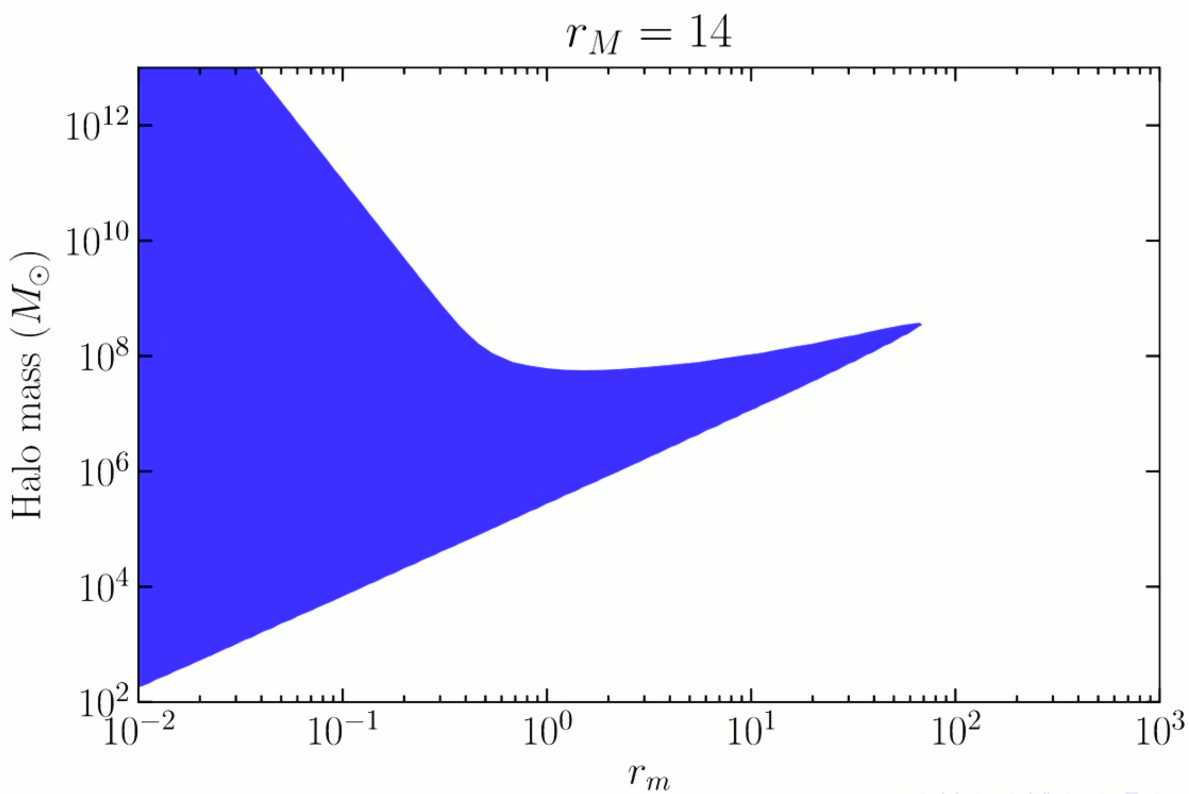
Halo Mass Function



Phase 0: Cooling and Collapse
Gurian, Ryan, Schon, Jeong, Shandera 2022

Basic Timescale Argument

Not all halos cool: if $t_c < t_{ff}$, collapse can occur (Buckley+ 2018)

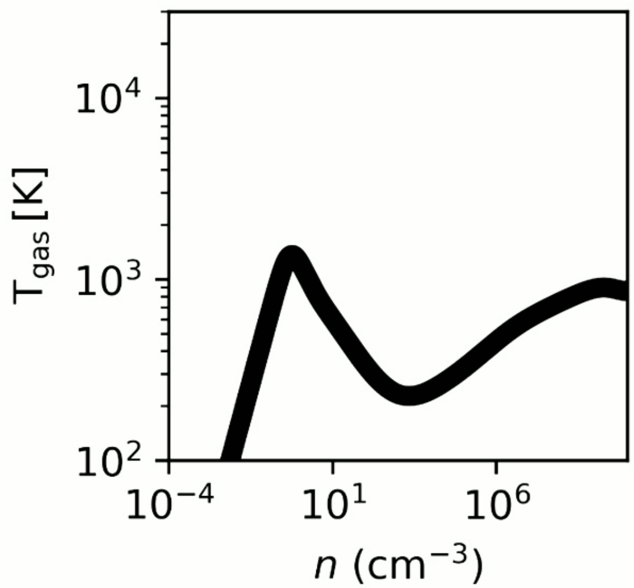


Improvement: Solve the Chemical Network

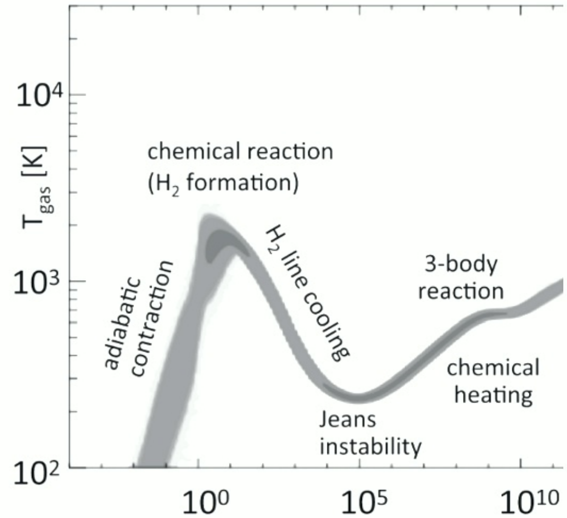
#	Reaction	σ	Re-scaling pre-factor
1	$p + e \to \text{H} + \gamma$	$\frac{\alpha^5}{\text{K.E.}(\text{K.E.}+\Delta E)}$	$r_\alpha^2\, r_m^{-2}$
2	$\text{H} + \gamma \to p + e$	$\mu\, \alpha^5 \frac{1}{(\text{K.E.}+\Delta E)^3}$	$r_\alpha^5\, r_m$
3	$\text{H} + e \to \text{H}^- + \gamma$	$\frac{\alpha}{\mu^2}\ \frac{\Delta E^{1/2}\, \text{K.E.}^{1/2}}{(\text{K.E.}+\Delta E)}$	$r_\alpha^2\, r_m^{-2}$
4	$\text{H}^- + \gamma \to \text{H} + e$	$\frac{\alpha}{\mu}\, \frac{\Delta E^{1/2} K^{3/2}}{(\text{K.E.}+\Delta E)^3}$	$r_\alpha^5\, r_m$
5	$\text{H}^- + \text{H} \to \text{H}_2 + e$	$\sqrt{\frac{\alpha\, a_0^3}{\text{K.E.}}}$	$r_\alpha^{-1}\, r_m^{-3/2}\, r_M^{-1/2}$
7	$\text{H}^- + p \to 2\text{H}$	$\alpha\, a_0^2 \sqrt{\mu}\, \frac{\sqrt{\text{K.E.}+\Delta E}}{\text{K.E.}\, \Delta E}$	$r_\alpha^{-3}\, r_m^{-3}$
8	$\text{H} + p \to \text{H}_2^+ + \gamma$	$\frac{(\text{K.E.}+\Delta E)^3 \alpha^4}{E_{\text{H}}^3 \text{K.E.}^{3/2} M^{1/2}}$	
9	$\text{H}_2^+ + \gamma \to \text{H} + p$	$\left(\frac{\mu\, v}{h\, \nu}\right)^2\ \frac{(\text{K.E.}+\Delta E)^3 \alpha^4}{E_{\text{H}}^3 \text{K.E.}^{3/2} M^{1/2}}$	$r_\alpha^5\, r_m^{1/2}\, r_M^{1/2}$
10	$\text{H}_2^+ + \text{H} \to \text{H}_2 + p$	$\sqrt{\frac{\alpha\, a_0^3}{\text{K.E.}}}$	$r_\alpha^{-1}\, r_m^{-3/2}\, r_M^{-1/2}$
13	$\text{H}_2^+ + \text{H}_2 \to \text{H}_3^+ + \text{H}$	—"—	—"—
15	$\text{H}_2 + p \to \text{H}_2^+ + \text{H}$	—"—	—"—
20	$\text{H}_3^+ + e \to \text{H} + \text{H}_2$ $\frac{\alpha\, a_0}{\text{K.E.}}$	$r_\alpha^{-1}\, r_m^{-2}\, r_M$	
*	$\text{H}_2 + \text{H} \to 3\text{H}$	a_0^2	$r_\alpha^{-1}\, r_m^{-3/2}\, r_M^{-1/2}$
3B1	$3\text{H} \to \text{H}_2 + \text{H}$	$a_0^2 \left[\frac{n_{\text{H}_2}}{n_{\text{H}}^2}\right]_{\text{LTE}}$	$r_\alpha^{-4}\, r_m^{-4}\, r_M^{-1}$
3B2	$\text{H}_2 + 2\text{H} \to 2\text{H}_2$	—"—	—"—
3B3	$2\text{H} + \text{H}^+ \to \text{H}_2 + \text{H}^+$	—"—	—"—
3B4	$2\text{H} + \text{H}^+ \to \text{H}_2^+ + \text{H}$	—"—	—"—

What About Gravity?

One zone, $\dot{\rho} = \rho / t_{ff}$



State of the art 3D sim (Yoshida 2019)

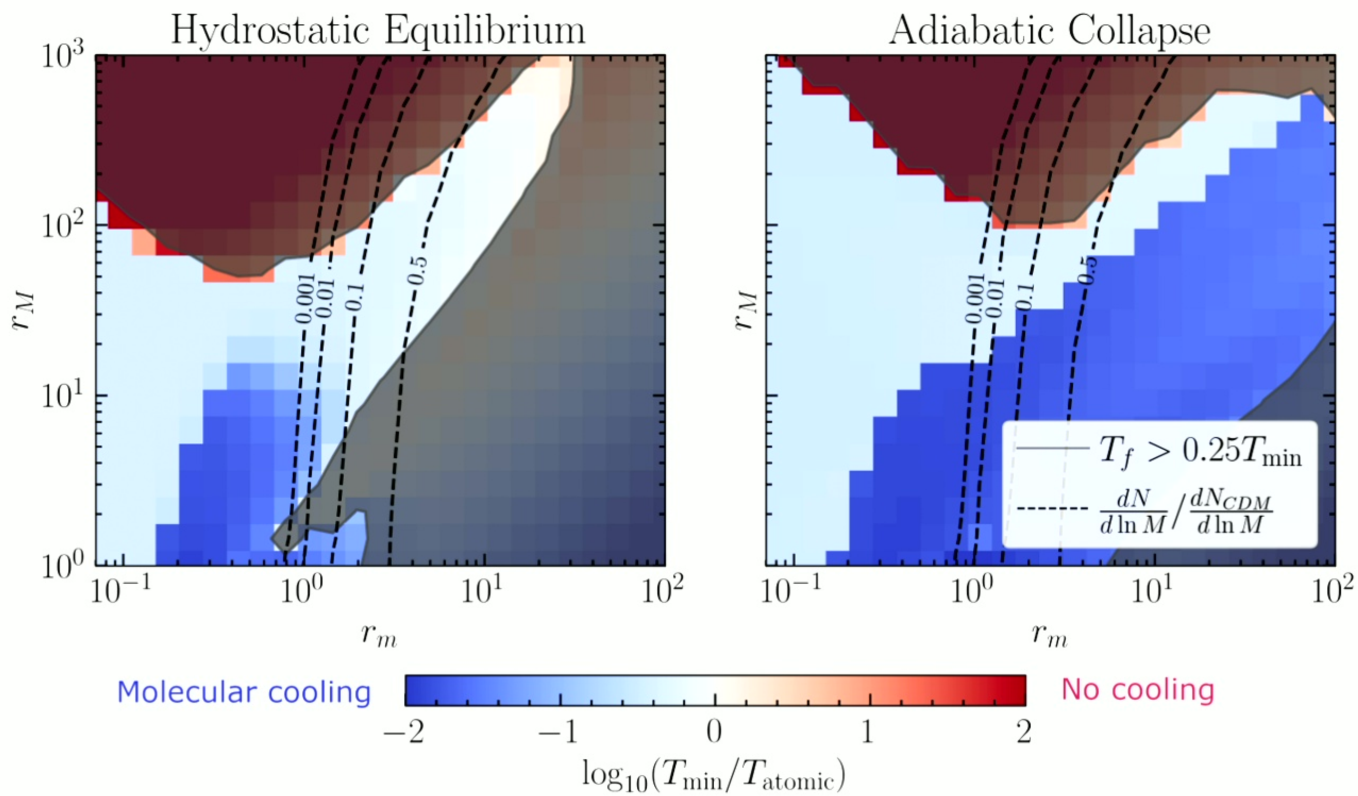


Setup

Using DarkKROME (Ryan+ 2022), let's apply this tool to ADM with:

- $r_\alpha = 1$ (strong enough but not too strong)
- $\xi = 5 \times 10^{-3}$ (avoid large scale acoustic oscillations)
- $M_{halo} = 10^8 \, \mathrm{M}_\odot$ (smallest virialized halos for $\xi \sim 10^{-3}$)
- $r_M > 1$ (avoid self-scattering constraint, make small black holes)

The Minimum Temperature



Minimum Temperature to Minimum Mass

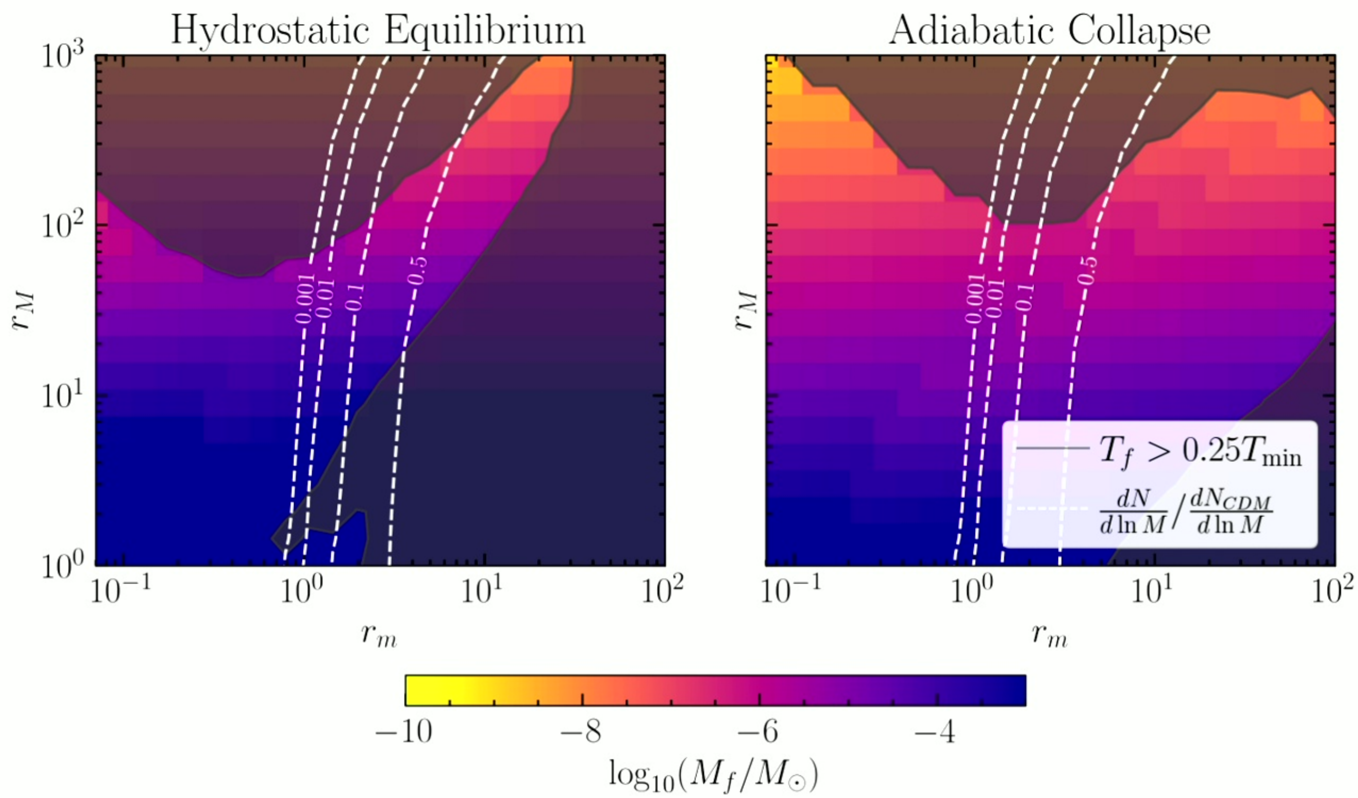
$$M_J \approx \left(\frac{\pi k T}{G m_p r_M}\right)^{3/2} \rho^{-1/2}.$$

Lower bound (Rees 1976):

$$M_{\min} > \left(\frac{\hbar c}{G}\right)^{3/2} \left(\frac{1}{m_p r_M}\right)^2 \left(\frac{kT}{r_M m_p}\right)^{1/4} \approx M_c \left(\frac{kT}{r_M m_p}\right)^{1/4}$$

The minimum fragment mass *before* accretion!

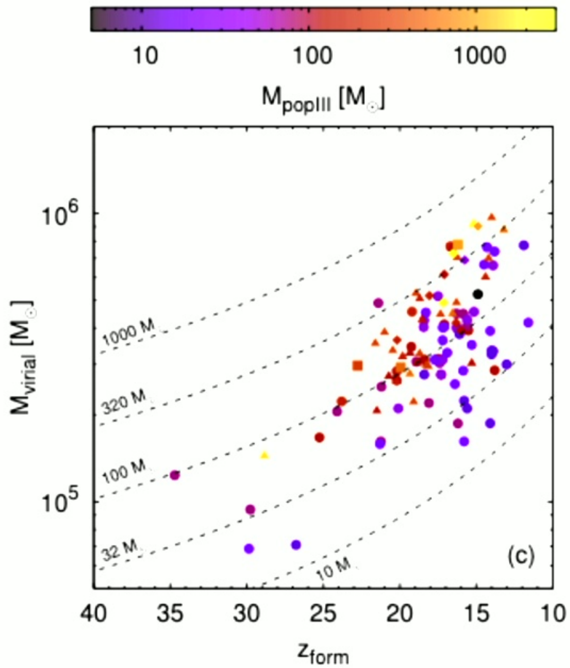
Minimum Mass



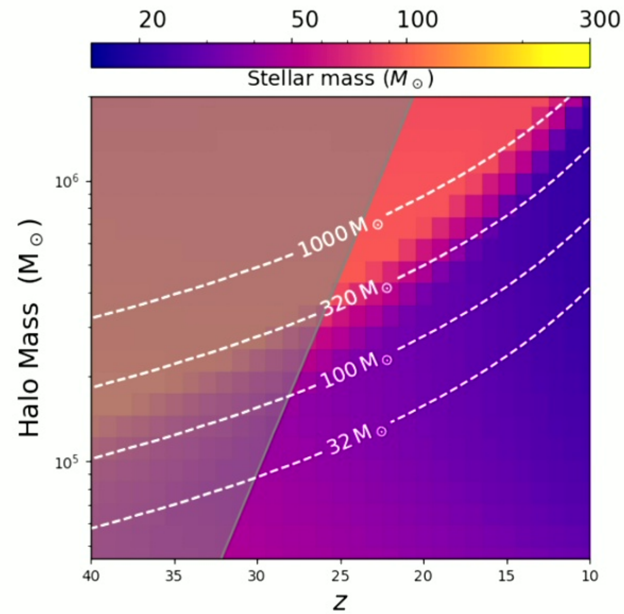
Phase 1: Accretion and Feedback

Let's start with the baryons

Figure: Hirano 2013



Zero Metallicity in Zero CPU Hours (in prep):



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)
- A large part of the ADM parameter space is prone to small-scale ($\ll \mathrm{M}_\odot$) fragmentation