Title: Dark and visible structures with dissipative dark matter

Speakers: Sarah Shandera

Collection: Dark Matter, First Light

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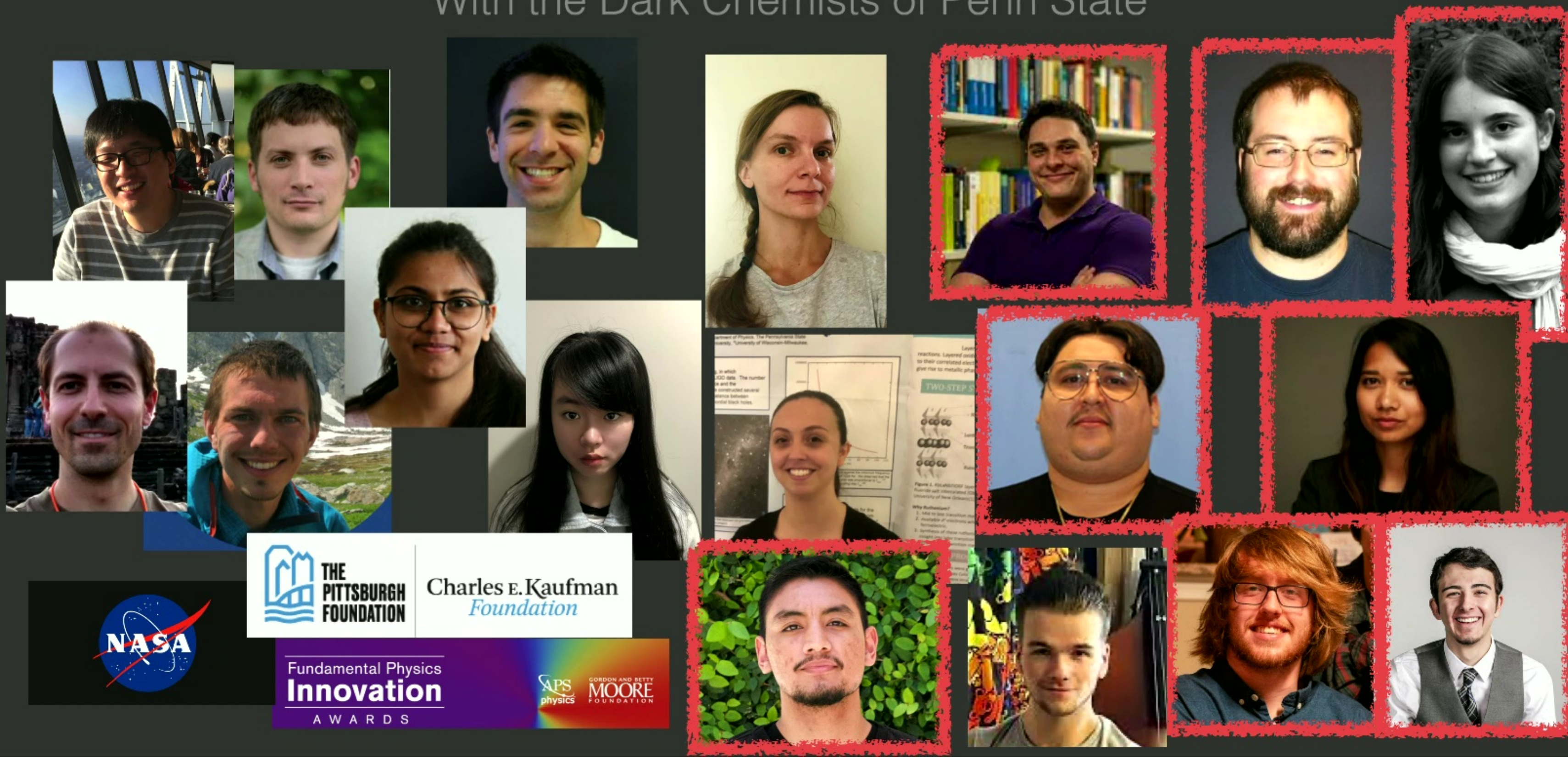
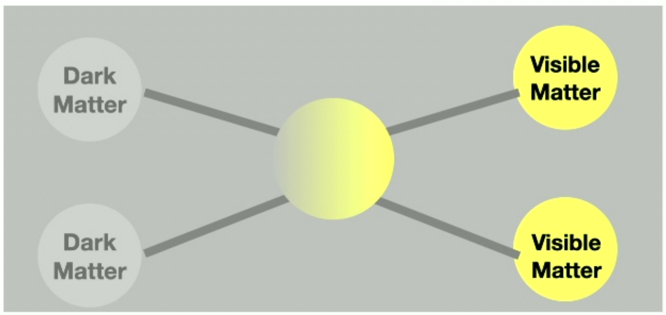
URL: https://pirsa.org/24020069

Dark and Visible Structures with Dissipative Dark Matter

Sarah Shandera
With the Dark Chemists of Penn State

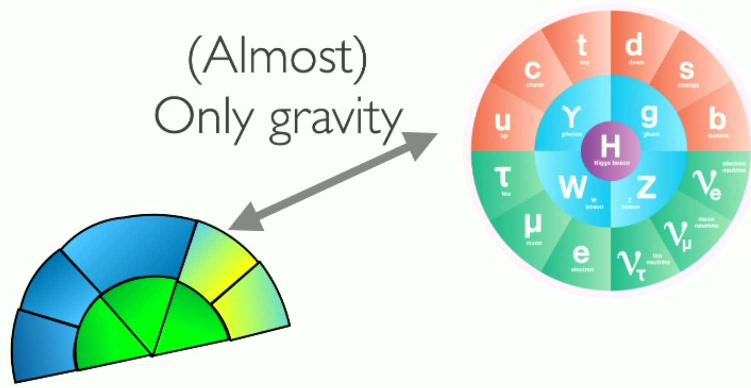


A different lens for dark matter



Most important interaction is with the Standard Model

- Or -



Most important interactions are between dark matter particles

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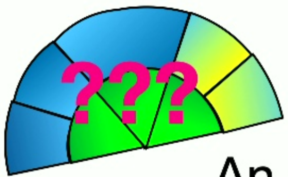


Complex dark matter?

An old idea:

1965: Nishijima, Saffouri "CP Invariance and the Shadow Universe"

1966: Kobzarev, Okun, Ya, Pomeranchuk "On the possibility of experimental observation of mirror particles" (2014 review, Blinnikov, for Pomeranchuk's 100th birthday)

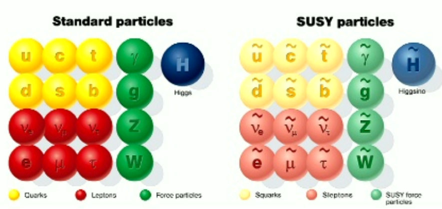
1985: Gross, Harvey, Martinec, Rohm "Heterotic String" ("*shadow matter*")

1986: Goldberg, Hall "A New Candidate for Dark Matter" (electromagnetic interactions with visible matter)

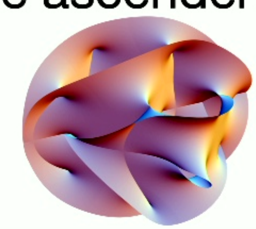
1996: Mohapatra, Teplitz ("Structures in the Mirror Universe")

......

Went under the radar while these ideas were ascendent:



(WIMPs)



(Axions)

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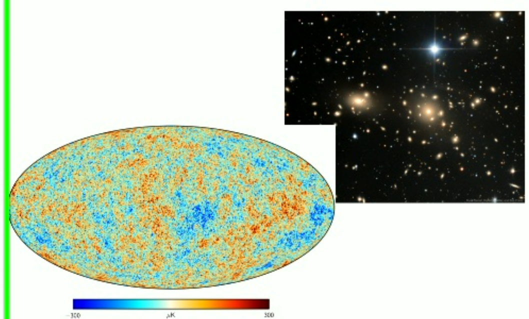
Where are the cleanest gravity-only probes of DM microphysics?



10^4 Mpc — 1 Mpc — 1 kpc — // — 1 km

Large-Scale structure
Linear physics, clean probes

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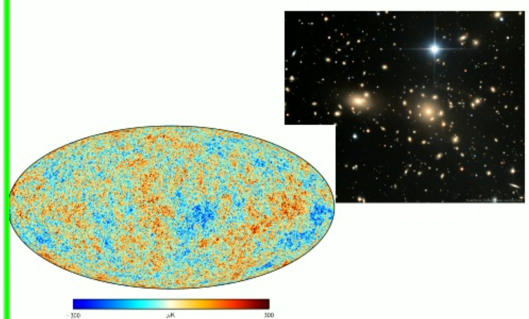
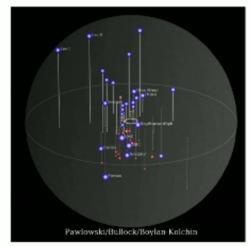
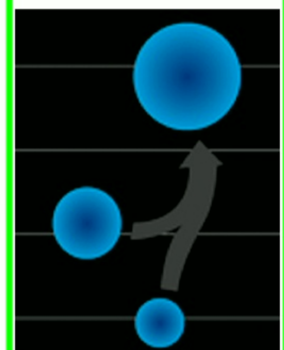
Where are the cleanest gravity-only probes of DM microphysics?



Simulations vs. Observations



(Bullock, Boylan-Kolchin, 1707.04256)



10^4 Mpc 1 Mpc 1 kpc 1 km

Large-Scale structure
Linear physics, clean probes

Mid-Scale structure
Many complexities from visible matter.
Hints that more complex dark matter is better.

Novel Compact objects
Existence is a clean probe

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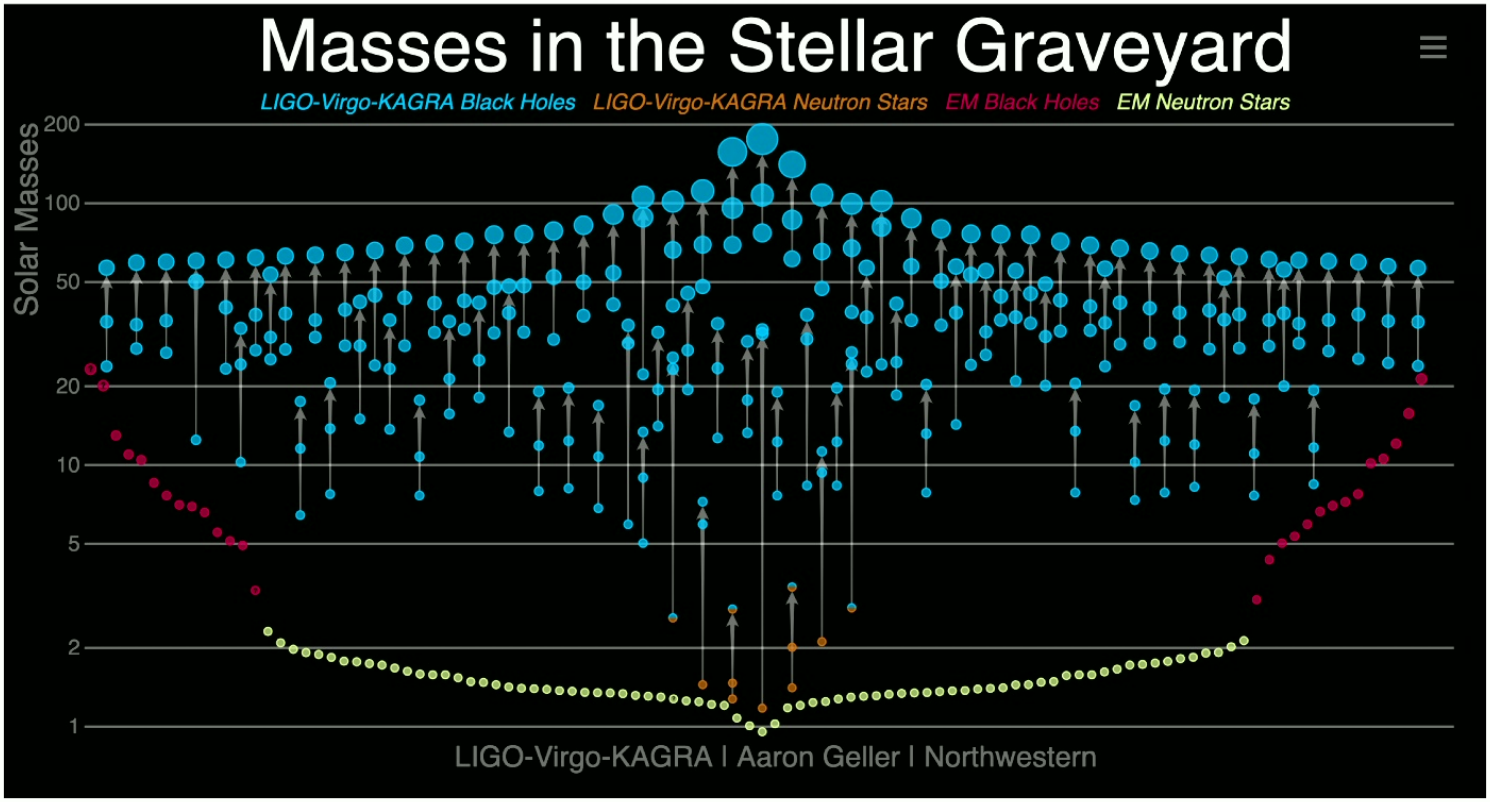
Gravity-only probes of microphysics



+O4!

LIGO-Virgo-KAGRA / Aaron Geller / Northwestern

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A simple dark sector with distinctive black holes

Dark "electron" $0.01 \lesssim \frac{m}{m_{\rm electron}} \lesssim 100$

Dark "proton" $1 \lesssim \frac{M}{m_{\rm proton}} \lesssim 1000$

Dark "photon" massless

Dark fine structure constant $0.1 \lesssim \frac{\alpha}{\alpha_{\rm EM}} \lesssim 2$

→ Interesting BH masses

$$M^{\rm Dark}_{\rm Chand.} \propto 1 M_{\odot} \left(\frac{m_{\rm prot.}}{M}\right)^2$$

Dark "hydrogen"

→ Cooling channels

→ Allows BHs to form dynamically from dark matter

No nuclear physics; No coupling to the standard model

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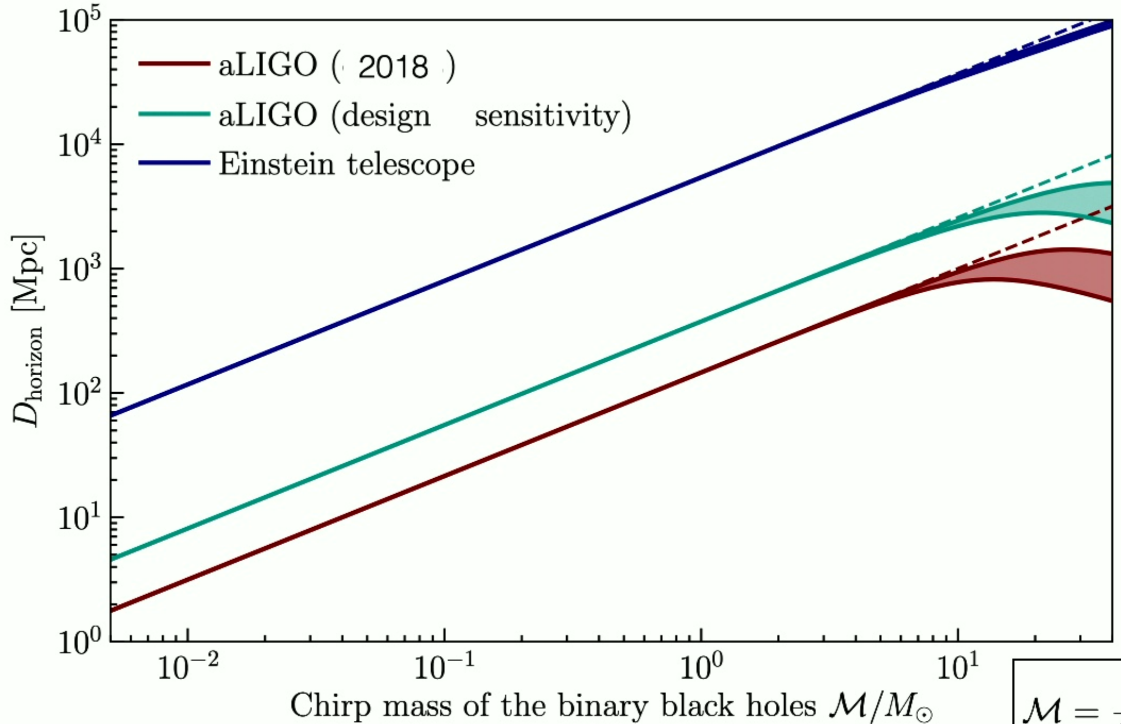
Clean new physics discovery space below ~1 solar mass



$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

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The estimate from atomic dark matter was promising:

m_X [GeV]	m_c [keV]	$M^{\rm dark}_{\rm Chand.}$ $[10^{-5} M_\odot]$	$M_{\rm DBH}$ $[M_\odot]$	Rates per year: aLIGO (full)	Rates per year: Einstein T.	$m_1 < 1.4$ [%]	$m_1, m_2 < 1.4$ [%]
62	31	33	$0.0068 - 0.68$	0.020 (2.0)	60 (6000)	100%	100%
48	47	56	$0.016 - 1.6$	0.11 (11)	330 (33k)	99%	79%
32	70	125	$0.054 - 5.4$	1.1 (110)	3500 (350k)	53%	9.3%
16	140	500	$0.43 - 43$	22 (2200)	92k (9200k)	9.8%	0.14%

Fraction of dark matter in Dark Black Holes: $f_{\rm cool} \times f_{\rm form.\,eff.} = 10^{-5}\ (10^{-3})$

S. Shandera, D. Jeong, H.Grasshorn Gebhardt (1802.08206, *PRL* **120**, 2018)

Compact objects in other dissipative scenarios: Chang et al, Bramante et al, Fernandez et al

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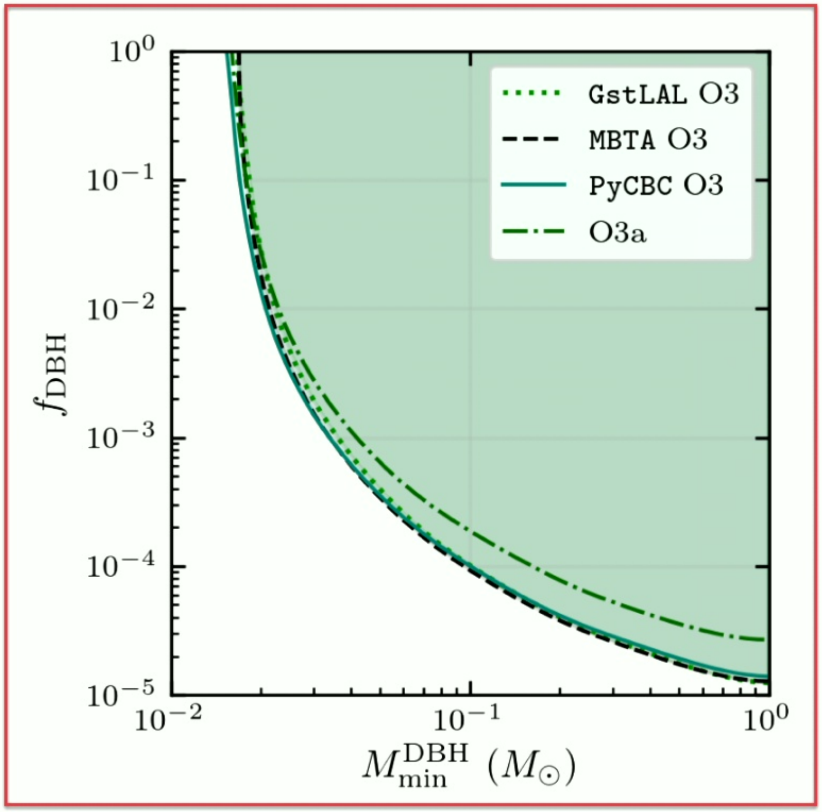
Search for sub-solar mass black holes

- Search for sub-solar mass black holes: so far, no detections

$m_1 \in [0.2, 10]$

$m_2 \in [0.2, 1]$

$$0.1 < q = \frac{m_2}{m_1} < 1.0$$



Fourth observing run is in progress

LIGO, Virgo, KAGRA, D. Jeong, S. Shandera; (2212.01477, MNRAS; 2109.12197, PRL; 1904.08976 PRL;1808.04771 PRL); R. Magee et al 1808.04772, PRD;

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GW190425: an intriguing event

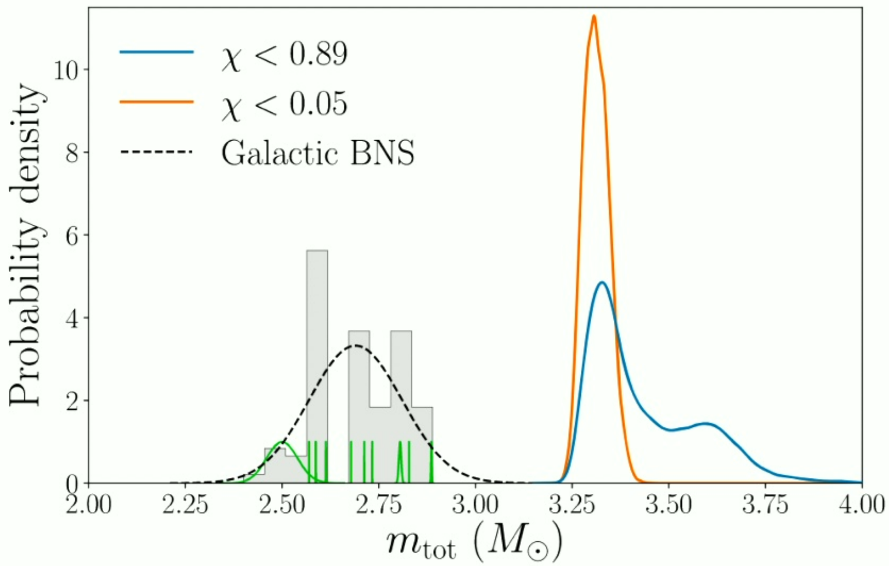

Figure 5. Total system masses for GW190425 under different spin priors, and those for the 10 Galactic BNSs from Farrow et al. (2019) that are expected to merge within a Hubble time. The distribution of the total masses of the latter is shown and fit using a normal distribution shown by the dashed black curve. The green curves are for individual Galactic BNS total mass distributions rescaled to the same ordinate axis height of 1.

LVC collaboration paper 2001.01761

$\gtrsim 5\sigma$ Outlier from known BNS systems

Component masses:

$$1.12 - 2.52\, M_\odot$$

"Neutron star" label currently applied based on mass alone, in absence of EM counterpart

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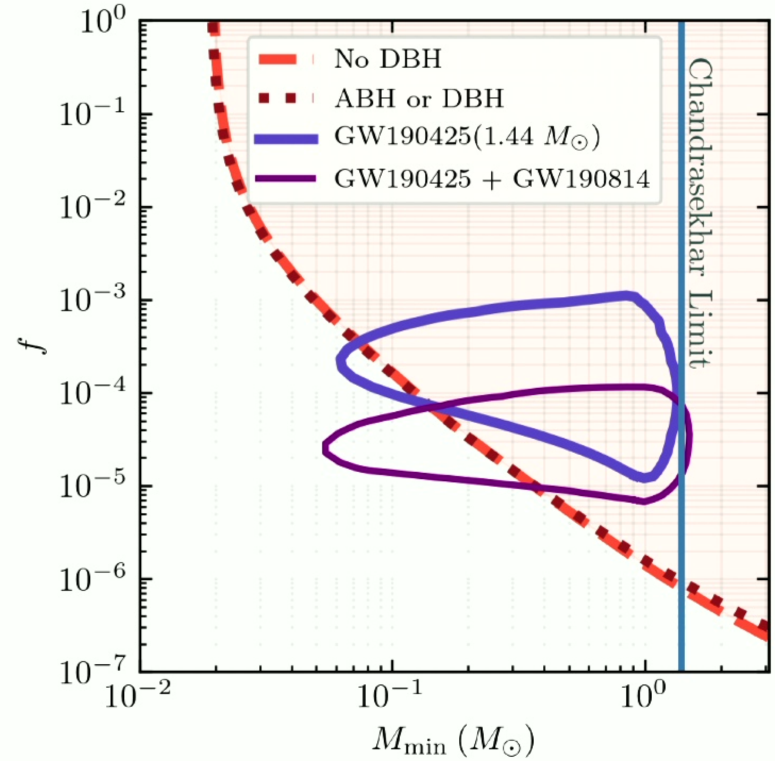
If GW190425 is a dark black hole event:

Rates ➡ Limits on source population



D. Singh, M. Ryan, R. Magee, T. Akhter, S. Shandera, D. Jeong, C. Hanna (2009.05209)

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If GW190425 is a dark black hole event:

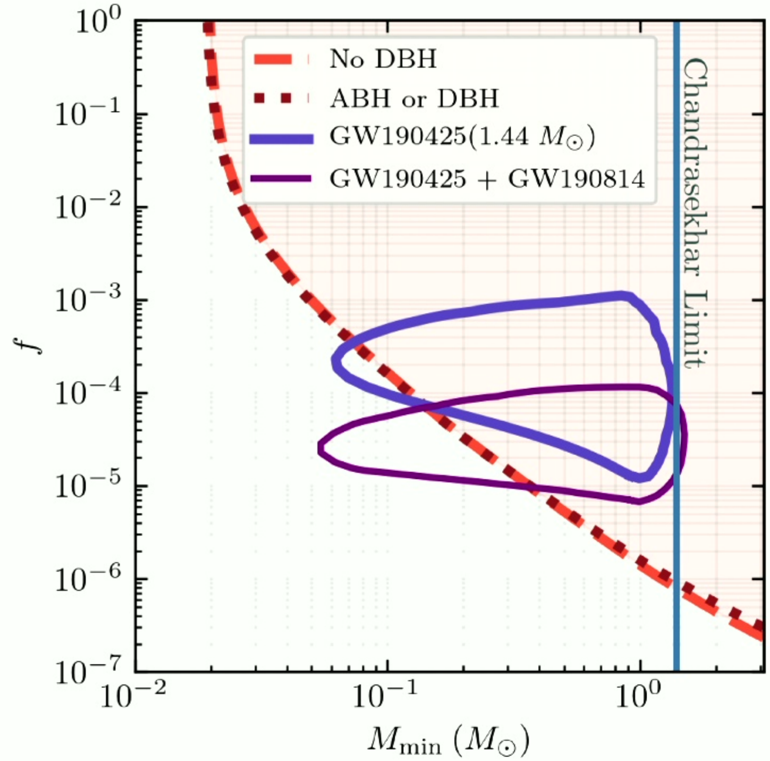
Rates ➡ Limits on source population

(A1) $M_{\rm min} \to M_{\rm D.Chand.} \to M_{\rm heavy\, fermion}$

$$M^{DM}_{\rm Chand.} < 1.4 M_{\odot}\,, \quad 99.9\%{\rm C.L.}$$

(A2) $M_{\rm min} \to M_{\rm min\, gas\, fragment} \to \Delta E_{\rm molecular}$

$$\Delta E_{\rm mol.} \sim 10^{-3}\,{\rm eV} \propto \frac{\alpha^2 m^2}{M}$$



D. Singh, M. Ryan, R. Magee, T. Akhter, S. Shandera, D. Jeong, C. Hanna (2009.05209)

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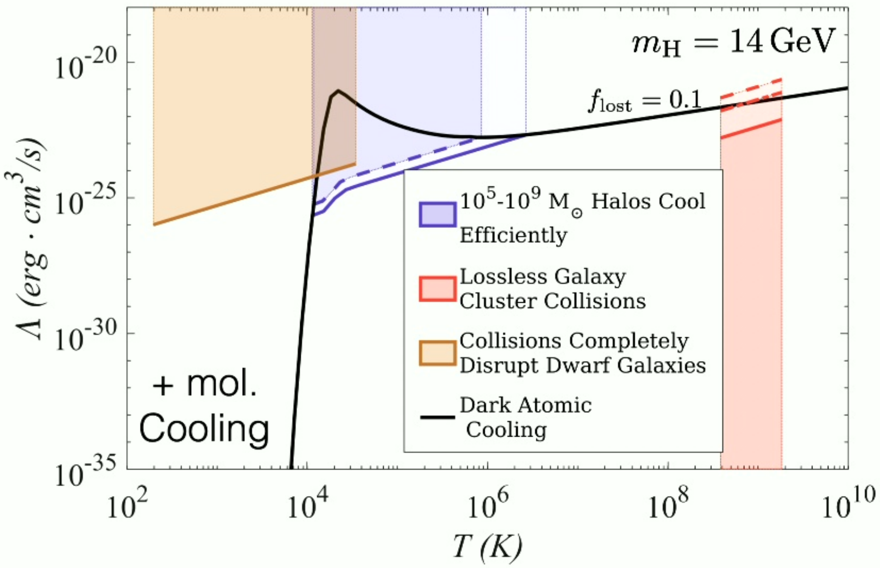
If GW190425 is a Dark Black Hole Event:

(B) Cooling rate (over number density) of dark matter

To form DBHs, need a minimum amount of cooling

Collisions in Bullet cluster give an upper bound on cooling (energy loss)



D. Singh et. al. 2009.05209

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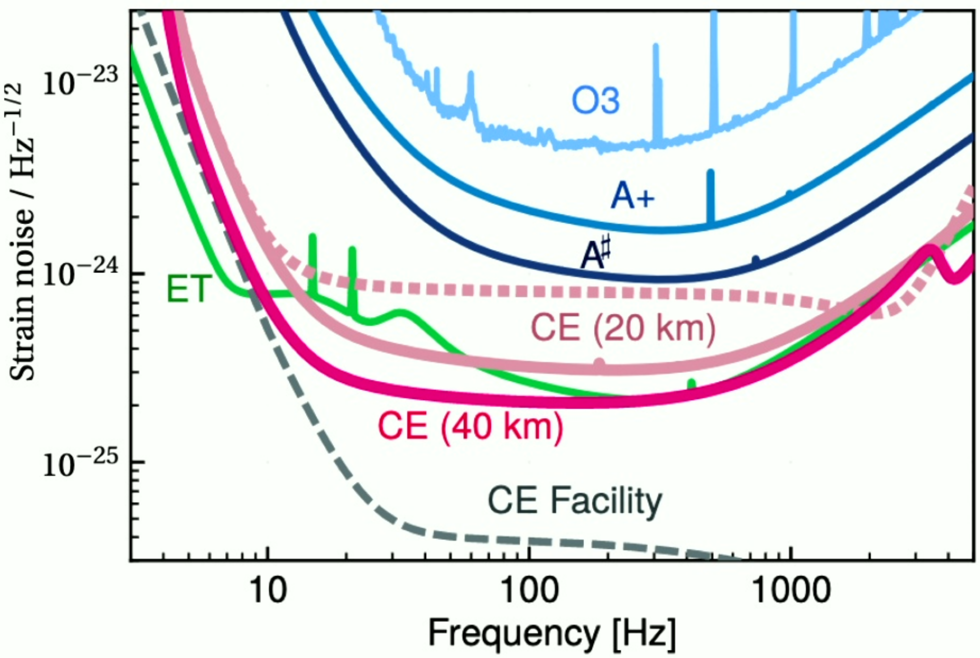
Outlook for sub-solar mass searches



Figures + Projections from 2307.10421

LIGO Observing run 4: O4a May 24, 2023 - Jan 16 2024
LIGO Observing run 4: O4b March 27, 2024 - Nov 2024

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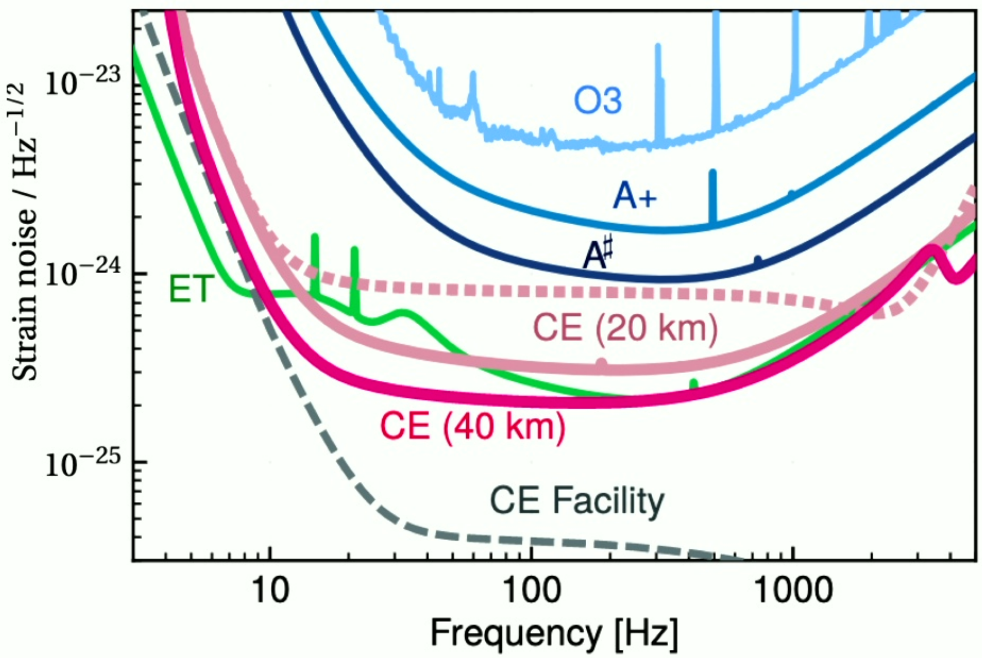
Outlook for sub-solar mass searches



Figures + Projections from 2307.10421

Novel compact more generally:

- Ryan and Radice, 2201.05626, dark white dwarfs
- Hippert et al, 2103.01965, dark neutron stars

LIGO Observing run 4: O4a May 24, 2023 - Jan 16 2024
LIGO Observing run 4: O4b March 27, 2024 - Nov 2024

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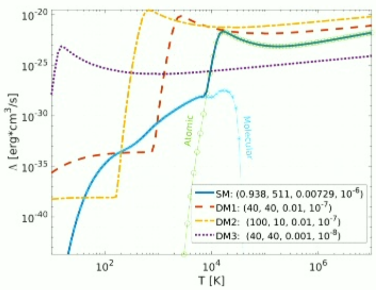
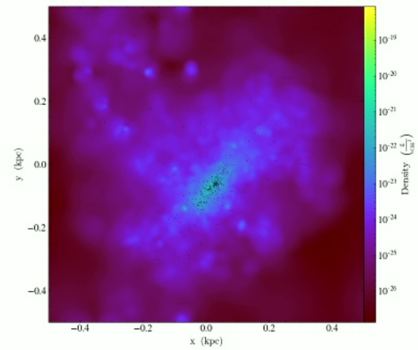
What next?

Particle Physics and Chemistry

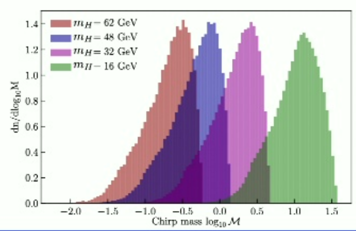


Hard!

Structure formation

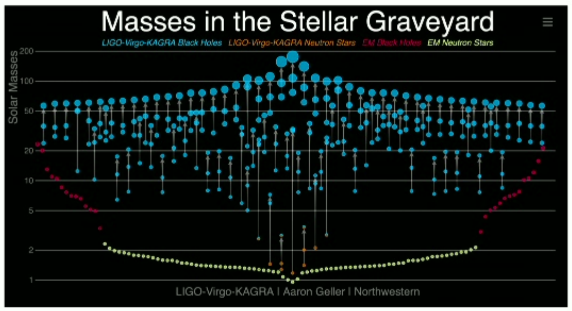


Population model for ultracompact objects



Not too hard

Gravitational wave data



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Prior work on atomic dark matter

Goldberg, Hall 1986
Ackerman et al 0810.5126
Feng et al 0905.3039
Kaplan et al 0909.0753, 1105.2073
Fan et al 1303.1521,1303.3271
Cyr-Racine et al 1209.5752, 1310.3278
Cline, Liu, Moore, Xue, 1311.6468
Foot, Vagnozzi 1409.7174, etc
Boddy et al, 1609.03592
Agrawal et al, 1610.04611
Ghalsasi and McQuinn, 1712.04779

Simulation work:

Vogelsberger et al 1805.03203
Huo et al 1912.06757
Todoroki et al 1711.11078
Shen et al, 2102.09580

Mirror dark matter:

Kobzarev et al, 1966,….more…..,
Mohapatra, Teplitz 1996 ("Structures in the Mirror Universe")
Mohapatra, Teplitz 1999 ("Mirror Matter MACHOs")
D'Amico et al, 1707.03419
Roux and Cline 2001.11504

Atomic physics of this model was known

Detailed rates for atomic processes calculated by Rosenberg and Fan, 1705.10341
Basic argument about cooling: Buckley and DiFranzo, 1707.03829

But molecular physics is crucial for early universe abundances and for understanding cooling

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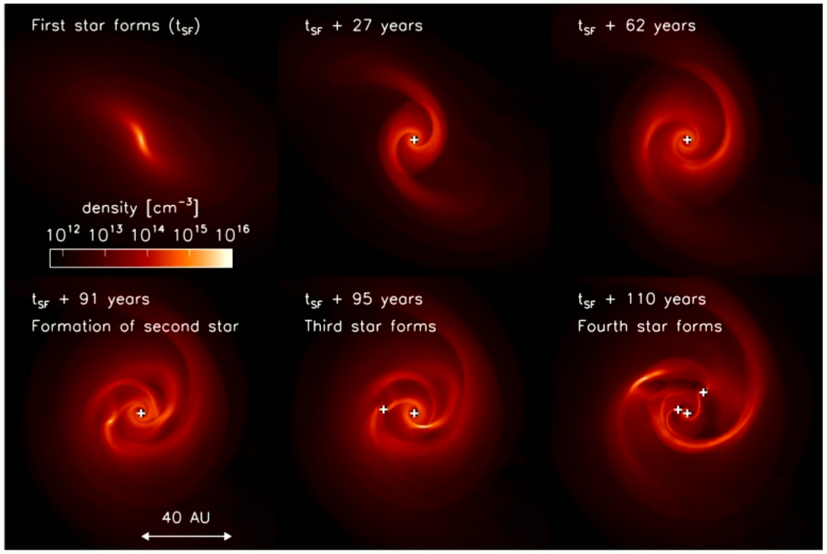
Why molecular physics?

First stars:

Fragmentation depends on coldest temperature the gas can reach



Haemmerlé et al, 2003.10533

Standard Model:

- Atomic cooling ~ 10^4 K
- Molecular cooling ~ 10^2 K

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Molecular physics

From first principles: solve the 4-body Schrödinger equation?

$$H\Psi(\mathbf{X}_A, \mathbf{X}_B; \mathbf{x}_1, \mathbf{x}_2) = E\Psi(\mathbf{X}_A, \mathbf{X}_B; \mathbf{x}_1, \mathbf{x}_2)$$

Easy to write down, hard to solve

$$H = -\frac{1}{2M}(\nabla_A^2 + \nabla_B^2) - \frac{1}{2m}(\nabla_1^2 + \nabla_2^2) + \alpha\left(\frac{1}{X_{AB}} + \frac{1}{x_{12}} - \frac{1}{x_{1A}} - \frac{1}{x_{2A}} - \frac{1}{x_{1B}} - \frac{1}{x_{2B}}\right)$$

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Molecular physics

Dimensional analysis!

Re-scale known standard model results using

$$r_m = \frac{m}{511\,\mathrm{keV}},\ r_M = \frac{M}{0.938\,\mathrm{GeV}},\ r_\alpha = \frac{\alpha}{137^{-1}}$$

James Gurian

Michael Ryan

Elastic cross-sections including molecular scattering Cline et al 1311.6468;
Some previous estimates in 1712.04779 (A. Ghalsasi, M. McQuinn)

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Molecular properties

For $m \ll M$, leading order re-scaling can be calculated:

Quantity	Dependence	Re-scaling
a_0 (Bohr radius)	$\frac{1}{\alpha\, m}$	$r_\alpha^{-1}\, r_m^{-1}$
$E_{\rm H}$ (atomic energy level spacing)	$m\,\alpha^2$	$r_\alpha^2\, r_m$
$E_{\rm rot}$ (Molecular rotational energy)	$\frac{\alpha^2\, m^2}{M}$	$r_\alpha^2\, r_m^2\, r_M^{-1}$
$E_{\rm vib}$ (Molecular vibrational energy)	$\frac{\alpha^2\, m^{3/2}}{M^{1/2}}$	$r_\alpha^2\, r_m^{3/2}\, r_M^{-1/2}$
$\mathbf{d}$ (dipole moment)	0	0
$A_{\rm rot}$ (quadrupolar rotational Einstein coefficient)	$\frac{\alpha^7\, m^6}{M^5}$	$r_\alpha^7\, r_m^6\, r_M^{-5}$
$A_{\rm vib}$ (quadrupolar vibrational Einstein coefficient)	$\frac{\alpha^7\, m^{7/2}}{M^{5/2}}$	$r_\alpha^7\, r_m^{7/2}\, r_M^{-5/2}$
p_{ij} (polarizability)	$a_0^3 = \frac{1}{m^3\, \alpha^3}$	$r_\alpha^{-3}\, r_m^{-3}$

The same re-scaling can be applied to more exact numerical results for standard model hydrogen.

2106.13245 (**M. Ryan, J. Gurian**, S. Shandera, D. Jeong)

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Not a simple system...

- Cooling rates need known atomic processes and
  - Molecular energy levels and transition rates
  - Populations, which means we need all scattering processes

2106.13245 (**M. Ryan, J. Gurian**, S. Shandera, D. Jeong)

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Not a simple system…

#	Reaction	Cross section source	σ	Re-scaling pre-factor $g(r_\alpha, r_m, r_M)$	b	Additional notes
1	$p + e \rightarrow \mathrm{H} + \gamma$(4.2)	Mo et al. (2010)	$\frac{\alpha^5}{\mathrm{K.E.}(\mathrm{K.E.}+\Delta E)}$	$r_\alpha^2\, r_m^{-2}$	$-0.62, -1.15$	a, b
2	$\mathrm{H} + \gamma \rightarrow p + e$(4.2)	Mo et al. (2010)	$\mu\, \alpha^5 \frac{1}{(\mathrm{K.E.}+\Delta E)^3}$	$r_\alpha^5\, r_m$	0.88, 0.35	c
3	$\mathrm{H} + e \rightarrow \mathrm{H}^- + \gamma$ (4.3)	de Jong (1972)	$\frac{\alpha}{\mu^2} \frac{\Delta E^{1/2}\, \mathrm{K.E.}^{1/2}}{(\mathrm{K.E.}+\Delta E)}$	$r_\alpha^2\, r_m^{-2}$	0.928	a, d
4	$\mathrm{H}^- + \gamma \rightarrow \mathrm{H} + e$	Armstrong (1963)	$\frac{\alpha}{\mu} \frac{\Delta E^{1/2} K^{3/2}}{(\mathrm{K.E.}+\Delta E)^3}$	$r_\alpha^5\, r_m$	2.13	c, d
5	$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + e$	Browne & Dalgarno (1969)	$\sqrt{\frac{\alpha\, a_0^3}{\mathrm{K.E.}}}$	$r_\alpha^{-1}\, r_m^{-3/2}\, r_M^{-1/2}$	0	e, f, g
7	$\mathrm{H}^- + p \rightarrow 2\mathrm{H}$ (4.4)	Bates & Lewis (1955)	$\alpha\, a_0^2 \sqrt{\mu}\, \frac{\sqrt{\mathrm{K.E.}+\Delta E}}{\mathrm{K.E.}\, \Delta E}$	$r_\alpha^{-3}\, r_m^{-3}$	$-\frac{1}{2}$	e, h
8	$\mathrm{H} + p \rightarrow \mathrm{H}_2^+ + \gamma$	Stancil et al. (1993)	$\frac{(\mathrm{K.E.}+\Delta E)^3 \alpha^4}{E_\mathrm{H}^3\, \mathrm{K.E.}^{3/2} M^{1/2}}$	$r_\alpha^2\, r_m^{-1}\, r_M^{-1}$	1.8	i
9	$\mathrm{H}_2^+ + \gamma \rightarrow \mathrm{H} + p$	Stancil et al. (1993)	$\left(\frac{\mu\, v}{h\, \nu}\right)^2 \frac{(\mathrm{K.E.}+\Delta E)^3 \alpha^4}{E_\mathrm{H}^3\, \mathrm{K.E.}^{3/2} M^{1/2}}$	$r_\alpha^5\, r_m^{1/2}\, r_M^{1/2}$	1.59	c, j
10	$\mathrm{H}_2^+ + \mathrm{H} \rightarrow \mathrm{H}_2 + p$(4.5)	Galli & Palla (1998)	$\sqrt{\frac{\alpha\, a_0^3}{\mathrm{K.E.}}}$	$r_\alpha^{-1}\, r_m^{-3/2}\, r_M^{-1/2}$	0	g
13	$\mathrm{H}_2^+ + \mathrm{H}_2 \rightarrow \mathrm{H}_3^+ + \mathrm{H}$	—"—	—"—	—"—	0	g
15	$\mathrm{H}_2 + p \rightarrow \mathrm{H}_2^+ + \mathrm{H}$(4.5)	—"—	—"—	—"—	0	g, j
20	$\mathrm{H}_3^+ + e \rightarrow \mathrm{H} + \mathrm{H}_2$	Draine (2011)	$\frac{\alpha\, a_0}{\mathrm{K.E.}}$	$r_\alpha^{-1}\, r_m^{-2}\, r_M$	-0.65	k
*	$\mathrm{H}_2 + \mathrm{H} \rightarrow 3\mathrm{H}$ (4.6)	Hard Sphere	a_0^2	$r_\alpha^{-1}\, r_m^{-3/2}\, r_M^{-1/2}$	0	l
3B1	$3\mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{H}$ (4.7)	Hard Sphere/Detailed Balance	$a_0^2 \left[\frac{n_{\mathrm{H}_2}}{n_\mathrm{H}^2}\right]_\mathrm{LTE}$	$r_\alpha^{-4}\, r_m^{-4}\, r_M^{-1}$	-1	j, m
3B2	$\mathrm{H}_2 + 2\mathrm{H} \rightarrow 2\mathrm{H}_2$ (4.7)	—"—	—"—	—"—	-1	j, m
3B3	$2\mathrm{H} + \mathrm{H}^+ \rightarrow \mathrm{H}_2 + \mathrm{H}^+$ (4.7)	—"—	—"—	—"—	-1	j, m
3B4	$2\mathrm{H} + \mathrm{H}^+ \rightarrow \mathrm{H}_2^+ + \mathrm{H}$ (4.7)	—"—	—"—	—"—	-1	j, m

$$\gamma = \langle \sigma v \rangle \propto g(r_\alpha, r_m, r_M) \left(\frac{T}{r_{\Delta E}}\right)^b$$

(But choose your favorite modern reaction rate for a more precise rate)

2106.13245 (**M. Ryan, J. Gurian**, S. Shandera, D. Jeong)
Some previous estimates in 1712.04779 (A. Ghalsasi, M. McQuinn)

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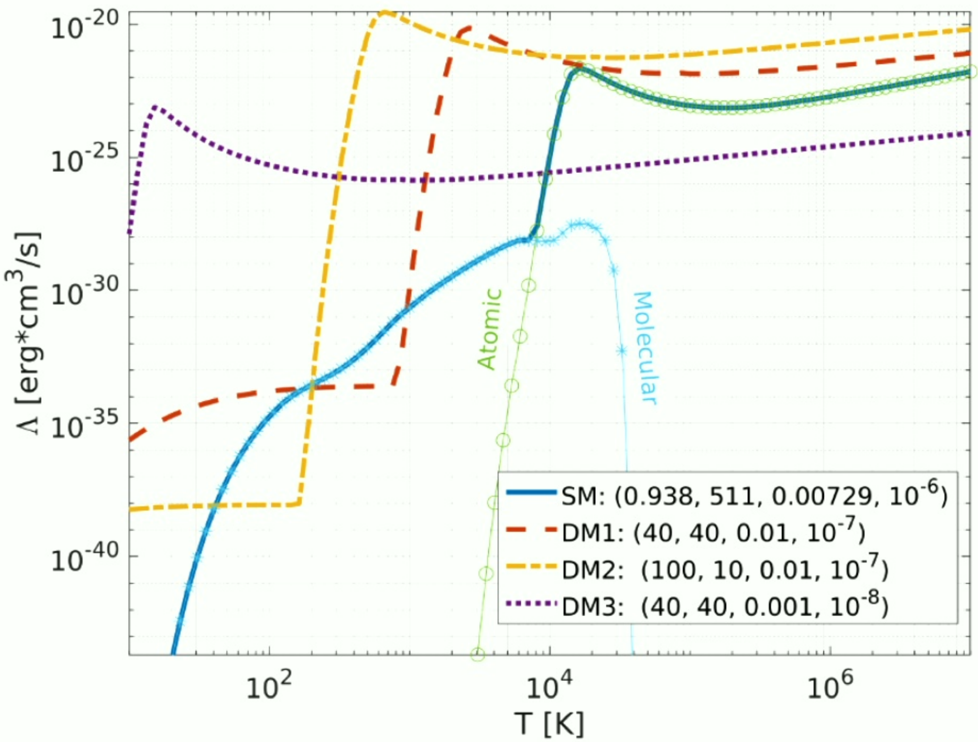
Atomic + molecular cooling rates



Legend: $(M[\mathrm{GeV}], m[\mathrm{keV}], \alpha, x_{\mathrm{H}_2})$

2106.13245 (**M. Ryan, J. Gurian**, S. Shandera, D. Jeong)

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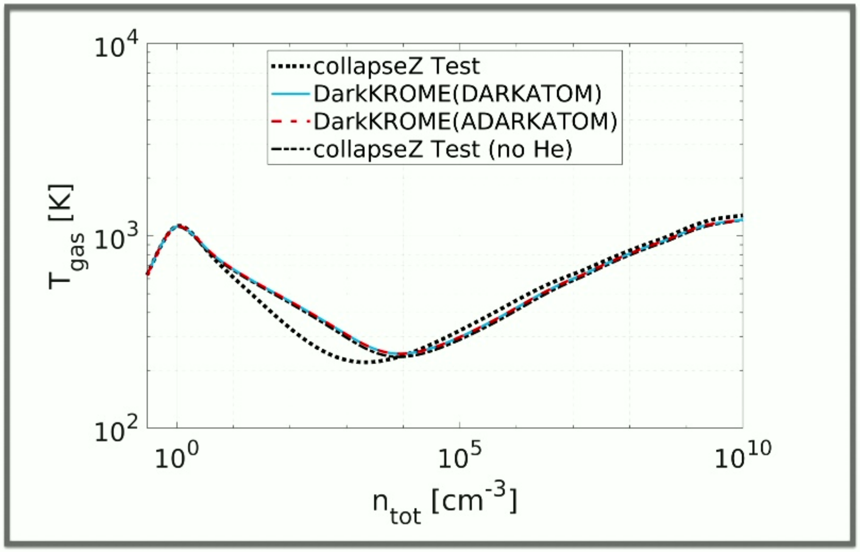
Putting the chemistry to work

Molecular, atomic abundances: **J. Gurian**, M. Ryan, D. Jeong, S. Shandera, 2110.11964
Homogeneous cosmology of the early universe (Recfast ++)
(https://github.com/jamesgurian/RecfastJulia)

DarkKROME: https://bitbucket.org/mtryan83/darkkrome
2110.11971 (**M. Ryan**, S. Shandera, J. Gurian, D. Jeong)

KROME: Grassi et al, 1311.1070 (kromepackage.org)



First-pass implications for gas cooling and compact objects: **Gurian, Ryan**, Schon, Jeong, Shandera 2209.00064

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Full simulations of dissipative models

Effects of dissipative dark matter on baryonic structures

- Couple the chemistry to a hydro-capable simulation structure:
  - Cosmological initial conditions + DarkKROME + GIZMO (P. Hopkins, 1409.7395)
- Add flexibility to work in hydrodynamical regime for dark matter only when it is appropriate
- Ideally: adaptable to other chemistry

Also: Roy, Shen, Lisanti, Curtin, Murray, Hopkins, 2304.09878, 2311.02148; 6% aDM

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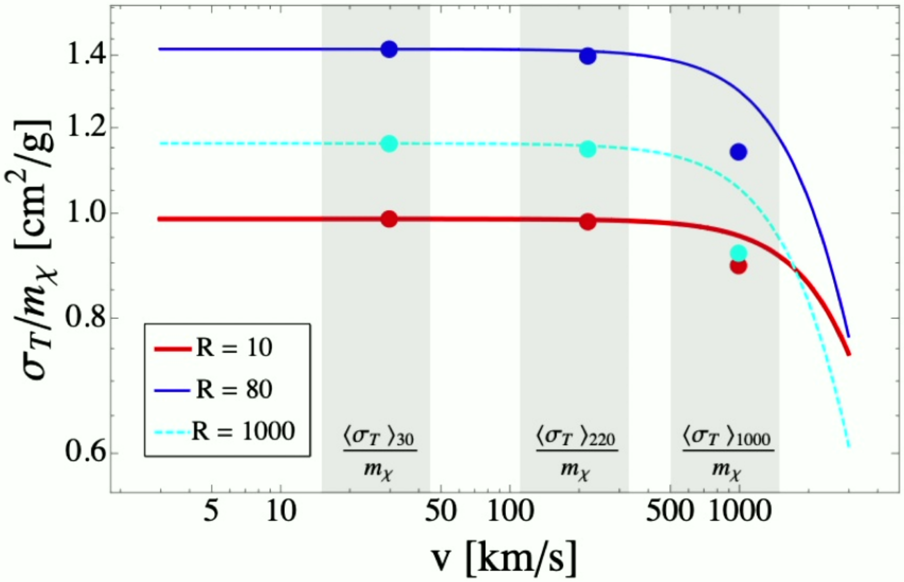
Dissipative dark matter in the elastic regime

Most simulations perturb the N-body dynamics using the elastic cross-section:



$$R = \frac{m_{\text{heavy}}}{m_{\text{light}}} \qquad \alpha_D = 0.05$$

Cyr-Racine et al, 1512.05344 (ETHOS); Cline et al 1311.6468

Shandera, Perimeter, Feb 2024

But there is a hydrodynamic regime….

Knudsen number - ratio of mean free path to fluid "cell"

$$K_n = \frac{l_{\rm mfp}}{l_s}$$

$$l_{\rm mfp} = \frac{1}{\sigma(v)\rho}$$

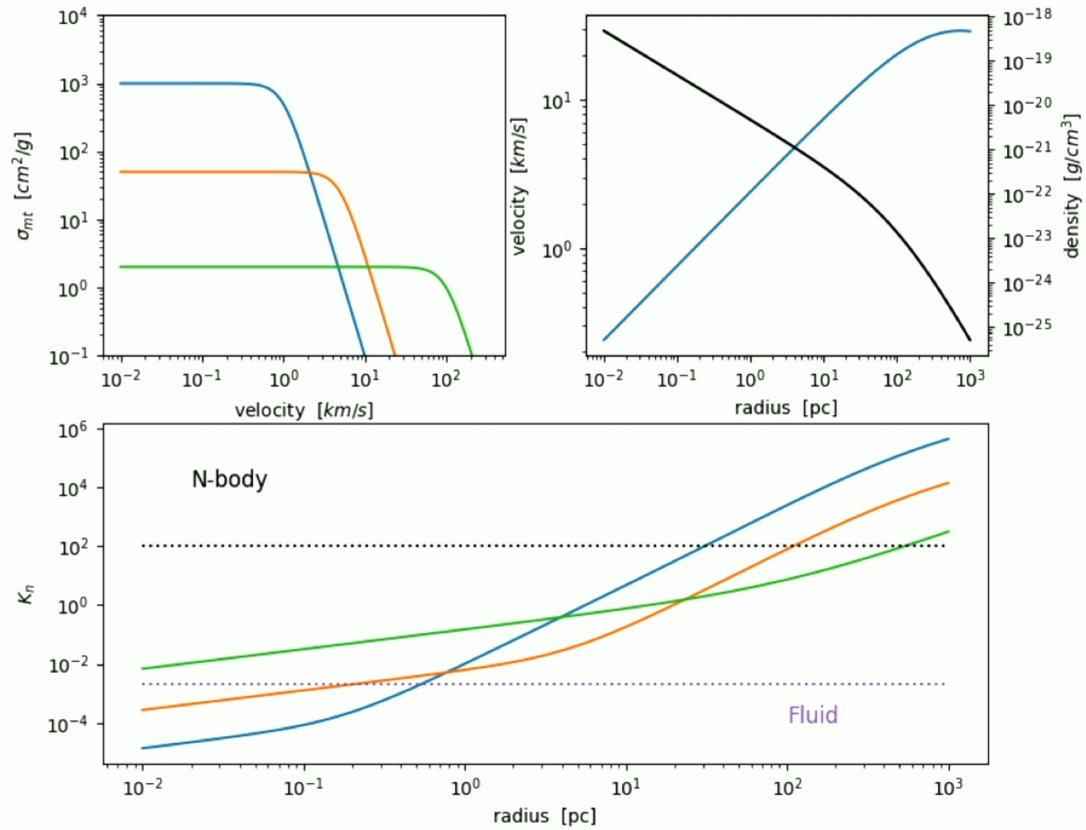
Hydrodynamics: $K_n \ll 1 \; (\sim \mathcal{O}(10^{-2}))$

Work led by Sarah Schon

Approximate kinematic regimes for a $10^8\, M_\odot$ halo.

$$K_n = \frac{l_{\rm mfp}}{l_s}$$

$$l_{\rm mfp} = \frac{1}{\sigma(v)\rho}$$



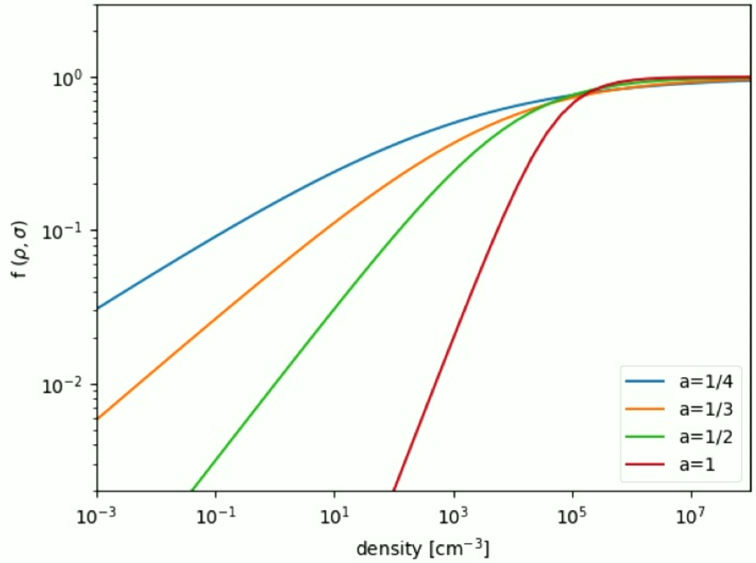
Figures: Sarah Schon

Numerical approach to atomic dark matter

First, introduce a simple interpolation between regimes:

$$f_{\mathrm{Kn}}(\sigma, \rho) = \frac{1}{1 + \left(\frac{\rho_{\mathrm{K}}}{\rho}\right)^{\alpha}}$$

include velocity dependence to
make it explicitly a function of the local
Knudsen number



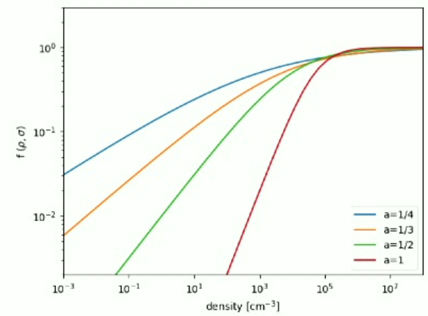
Work by Sarah Schon

Numerical approach to atomic dark matter

Then, use a boundary domain to connect hydro and kinematic regimes:

$$\frac{\mathrm{d}\mathbf{u}}{\mathrm{d}t} = (1 - f_{\mathrm{Kn}})\mathbf{F}_{kinetic} + f_{\mathrm{Kn}}\mathbf{F}_{fluid}$$

$$f_{\mathrm{Kn}}(\sigma, \rho) = \frac{1}{1 + (\frac{\rho_{\mathrm{K}}}{\rho})^{\alpha}}$$



Work by Sarah Schon

Prior implementations: Degond et al 2005, Journal of Computational Physics

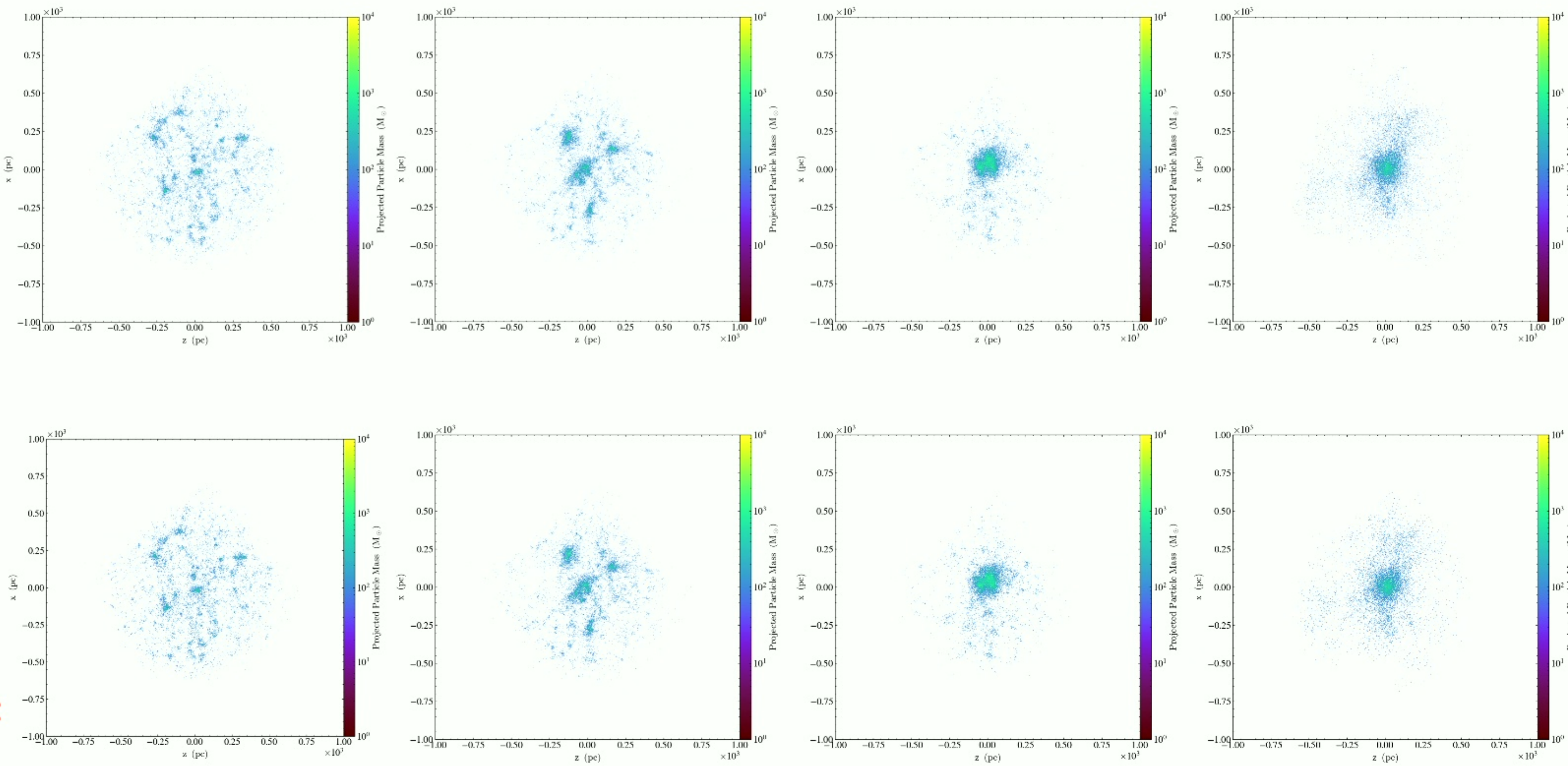
Comparison SIDM vs aDM (w/out cooling)

N-body limit

2^6 M_sol halo
M_dm = 90 M_sol

aDM with rho_k= 1e18 alpha = 8

N-body



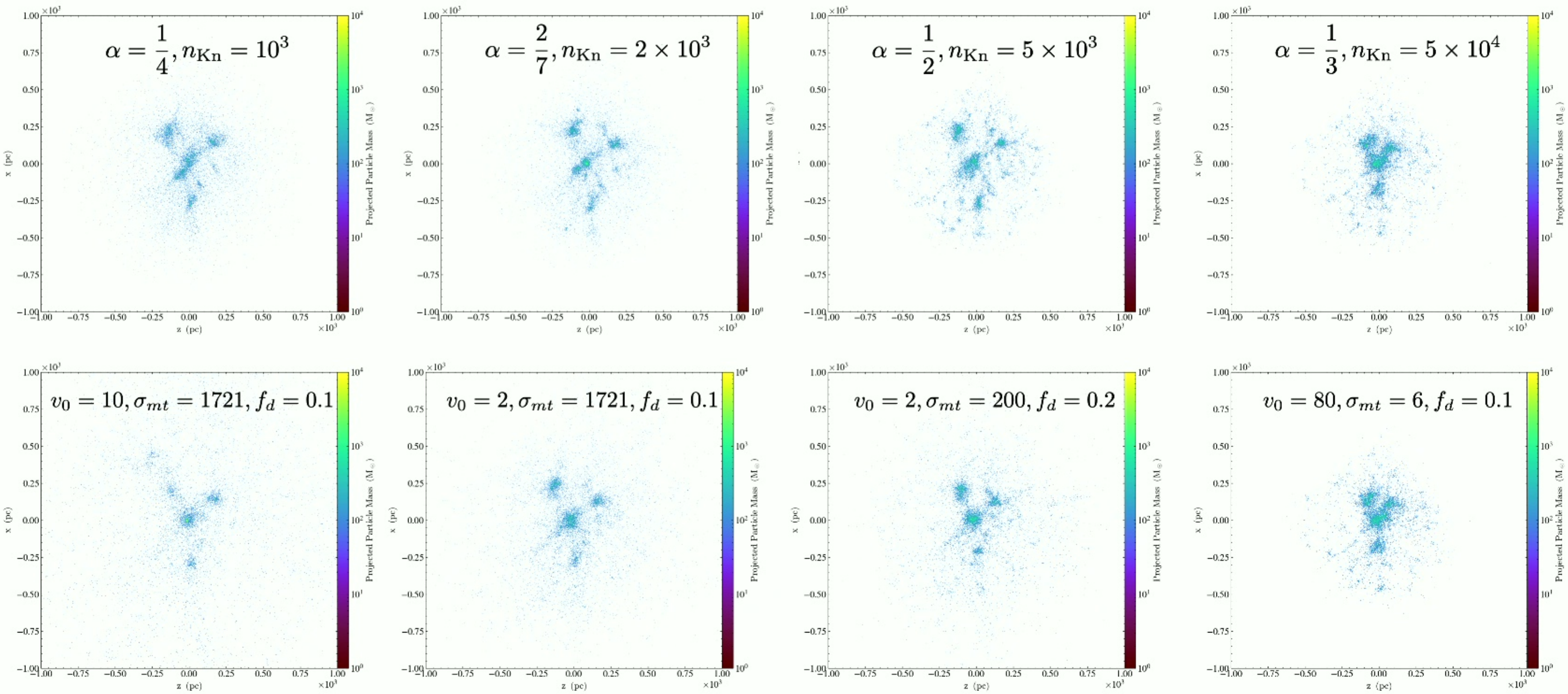
Simulations, slide: Sarah Schon

Comparison SIDM vs aDM hydro (w/out cooling)

"strong" interacting → **"weak" interacting**

aDM (No cooling)

SIDM

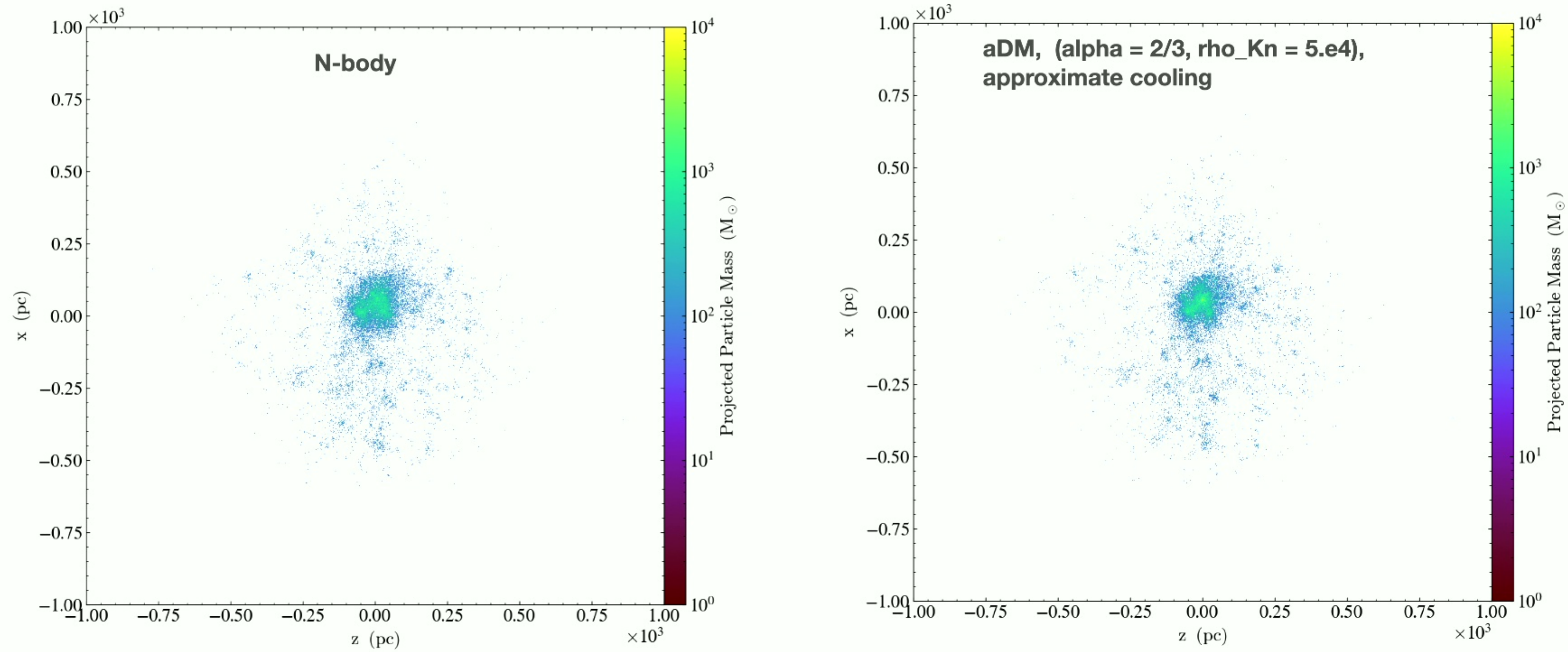


Slide and simulations: Sarah Schon

GIZMO SIDM implementation: 1706.07514

Comparison DM vs aDM hydro (w/ cooling)

Halo: dense aDM core formation (need very high resolution)



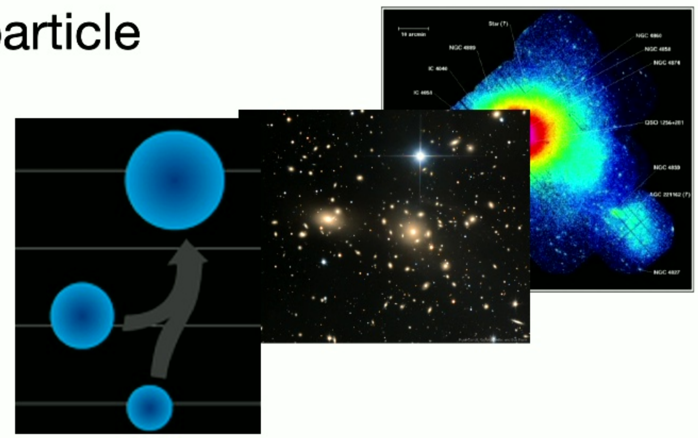
Simulations: Sarah Schon

Summary: toward DM microphysics from dark compact objects

Black Holes: Sensitive to/constraining for dark matter physics (far beyond primordial black holes)

Compact objects: a gravitational probe with particle physics power for dissipative dark matter (chemistry!)

- Fermion mass (Chandrasekhar limit)
- Cooling rate
- Molecular energy gap



Simulations with fully dissipative dark matter are within reach

Shandera, Perimeter, Feb 2024